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13 September 2019

Version of attached file:

Published Version

Peer-review status of attached file:

Peer-reviewed

Citation for published item:

Klein, Matthias and Israel, Holger and Nagarajan, Aarti and Bertoldi, Frank and Pacaud, Florian and Lee, Adrian T and Sommer, Martin and Basu, Kaustuv (2019) 'Weak lensing measurements of the APEX-SZ galaxy cluster sample.', *Monthly notices of the Royal Astronomical Society.*, 488 (2). pp. 1704-1727.

Further information on publisher's website:

<https://doi.org/10.1093/mnras/stz1491>

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Weak lensing measurements of the APEX-SZ galaxy cluster sample

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Accepted 2019 May 28. Received 2019 May 23; in original form 2018 April 24

ABSTRACT

We present a weak lensing analysis for galaxy clusters from the APEX-SZ survey. For 39 massive galaxy clusters that were observed via the Sunyaev–Zel’dovich effect (SZE) with the APEX telescope, we analyse deep optical imaging data from WFI (@2.2mMPG/ESO) and Suprime-Cam(@SUBARU) in three bands. The masses obtained in this study, including an X-ray selected sub-sample of 27 clusters, are optimized for and used in studies constraining the mass to observable scaling relations at fixed cosmology. A novel focus of our weak lensing analysis is the multicolour background selection to suppress effects of cosmic variance on the redshift distribution of source galaxies. We investigate the effects of cluster member contamination through galaxy density, shear profile, and recovered concentrations. We quantify the impact of variance in source redshift distribution on the mass estimate by studying nine sub-fields of the COSMOS survey for different cluster redshift and magnitude limits. We measure a standard deviation of ~ 6 per cent on the mean angular diameter distance ratio for a cluster at $z = 0.45$ and shallow imaging data of $R \approx 23$ mag. It falls to ~ 1 per cent for deep, $R = 26$ mag, observations. This corresponds to 8.4 per cent and 1.4 per cent scatter in M_{200} . Our background selection reduces this scatter by 20–40 per cent, depending on cluster redshift and imaging depth. We derived cluster masses with and without using a mass concentration relation and find consistent results, and concentrations consistent with the used mass–concentration relation.

Key words: gravitational lensing: weak – galaxies: clusters: general – cosmology: observations.

1 INTRODUCTION

Measuring the galaxy cluster mass function, $n(M, z)$, and internal structure of galaxy clusters can help in unveiling the basic nature of dark matter (Robertson, Massey & Eke 2017), the initial spectrum of the density perturbations and its evolution from the primordial universe till today (de Haan et al. 2016; Bocquet et al. 2019; Costanzi et al. 2018; Pacaud et al. 2018).

The formation of galaxy clusters is known to be sensitively connected to the cosmic expansion rate and the hierarchical structure formation (Rosati, Borgani & Norman 2002; Schuecker 2005; Voit 2005). Measuring the cluster mass function, therefore, offers a method to obtain constraints on the cosmological parameters additional to other known methods such as supernovae type Ia,

cosmic microwave background, or baryonic acoustic oscillations. Investigating the evolution of the mass function with redshift can also constrain the dark energy equation-of-state parameter ω_{DE} (Albrecht et al. 2006).

Several methods exist to measure the mass of galaxy clusters based on optical, X-ray, and sub-mm observations. Each of them have different advantages and disadvantages with respect to different science goals. In order to use the full constraining power of ongoing or planned cluster surveys for precision cosmology like SPT-3G (Benson et al. 2014), DES (Dark Energy Survey Collaboration et al. 2016), or eROSITA (Pillepich, Porciani & Hahn 2010), the knowledge of the mass calibration of the cluster observables and biases between these observables are crucial.

In contrast to methods using X-rays or the Sunyaev–Zel’dovich effect (SZE), weak gravitational lensing probes mass directly without assumptions on the dynamical state of the intracluster medium (ICM). Especially, in cluster mergers, the distribution

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and the dynamical state of the ICM can differ strongly from hydrodynamic equilibrium, making it difficult to determine reliable masses with SZE or X-rays. For this reason, weak gravitational lensing is preferentially used for calibrating mass-to-observable relations, which is the key motivation for the optical follow-up observations of the APEX-SZ galaxy clusters (Schwan et al. 2012; Bender et al. 2016).

The APEX-SZ experiment (Dobbs et al. 2006, 2012; Schwan et al. 2011) imaged the SZ decrement of galaxy clusters at 150 GHz using a 280-element Transition-Edge Sensor (TES) bolometer camera on the APEX 12-m telescope in Atacama Chile (Güsten et al. 2006). The experiment had 58 arcsec resolution over a 23 arcmin field of view. Apex-SZ observed 42 clusters over a total of 740 h in the period from 2005 to 2010.

Weak-lensing mass estimation have been actively pursued for numerous galaxy cluster samples (e.g. Postman et al. 2012; Applegate et al. 2014; Okabe & Smith 2016) of typical sample size of ~ 20 –50 clusters. In this paper, we present the weak gravitational lensing analysis of the APEX-SZ galaxy cluster sample (Bender et al. 2016; Nagarajan et al. 2018) comprising of 39 galaxy clusters in the redshift range of $z = 0.1$ to $z = 0.83$. Most of these clusters are X-ray selected. A sub-sample of 27 clusters form a complete galaxy cluster sample in X-ray luminosity and redshift space [see Nagarajan et al. (2018) for details]. One of the main purposes of measuring the cluster masses for this sample is to obtain reasonable constraints on mass–observable scaling relations. In particular, the subject matter of measuring the scaling between the Sunyaev–Zel’dovich effect and the cluster mass is studied in a companion paper by Nagarajan et al. (2018). Here, we describe the weak lensing analysis adopted for the cluster mass measurements that form the basis for such work.

To use weak lensing mass estimates for the mass calibration, the understanding and minimization of systematic effects is important. Weak-lensing measurements can suffer from systematic effects due to the contamination of the background sources from unlensed foreground or cluster member galaxies. This can result in an underestimation of the observed Einstein radius by a factor of 2.5 (Clowe & Schneider 2001; Bardeau et al. 2005). In the current weak lensing literature (Okabe & Smith 2016; Melchior et al. 2017; Medezinski et al. 2018; Dietrich et al. 2019), the selection of galaxies considered to be lensed sources is based on observations in two, three, or five, and more bands, reflecting three commonly used selection methods to identify background galaxies. While the first two methods rely on a reference catalogue and focus only on the exclusion of cluster member galaxies, the last method uses photometric redshift estimates that allow also to incorporate individual distance estimates for galaxies.

This work presents a three-filter method for background selection, which includes empirically derived photometric redshift estimates for each galaxy based on a comparison to a reference photo- z catalogue. This method is a mixed approach between the common three-filter methods [e.g. Medezinski et al. (2018)]; Dietrich et al. (2019) and photo- z methods. It reduces the impact of cosmic variance in the observed and reference field on the mass estimates. Furthermore, we give a detailed discussion of the analysis and results using a representative sub-sample of three galaxy clusters in the redshift range from $z = 0.15$ to 0.45 , which cover the redshift range of the majority of our cluster sample.

This paper is structured as follows: After a short discussion on cluster selection and data reduction in Section 2, we give a short introduction to weak lensing theory in Section 3. Section 4 is focused on the colour properties of galaxies and a lensing-optimized selection of background galaxies. In Section 5, we discuss the shear

modelling such as, the profile fitting, corrections for contamination, and the effect of cosmic variance on our data. Section 6 shows the lensing results and compares them with measurements from other publications. The last section, Section 7, presents the conclusions and shows future perspectives.

Throughout this paper we adopt a concordance Λ CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $h \equiv H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) = 0.7$.

2 CLUSTER SELECTION AND DATA REDUCTION

The galaxy clusters for the lensing follow-up observations were selected based on their observations with APEX-SZ SZE detector. The aim was to cover all SZE detections with $z < 1$ using a combination of dedicated observations with the Wide-Field Imager (WFI, Baade et al. 1999) and archive data from the same instrument and from Suprime-Cam (@Subaru) with at least three different filter bands. This goal was achieved with the only exception of a cluster at $z = 0.98$, resulting in a complete sample up to $z = 0.83$. The follow-up observations also includes clusters that were only observed but not detected by APEX-SZ, in order to ensure the completeness of an X-ray selected sub-sample (Nagarajan et al. 2018). To illustrate the data analysis, we select three clusters as examples. The clusters that we choose as examples are selected to reflect the typical redshift range, the difficulties in data reductions, and the optical data quality of the whole APEX-SZ sample.

The observation strategy with WFI was chosen to make optimal use of archival data in order to minimize the need of additional observations. For clusters where no archival existed, we observed with WFI in the B-123, V-89, and RC-162 (here after B , V , R) bands. The typical total exposure times for clusters at $z = 0.3$ are 12 000, 4500, and 15 000 s. In case of existing archival data, we only observed the missing bands or completed bands which had already some shallower data. This strategy results in a variation of filter bands used for the background selection and shear measurements. For example, for the analysis of RXC 1504, we use B , V , R band WFI observations for the photometry and the Suprime-Cam V band data for shear measurement.

Table 1 shows a summary of the data for the clusters presented in this publication. The basic data reduction steps (de-biasing, flatfielding, astrometry, absolute and relative photometry, and weighted co-addition) were conducted with THELI (Erben et al. 2005; Schirmer 2013) data reduction pipeline following closely the steps described in Israel et al. (2010). In addition to these steps described above, we used the outlier rejection option in THELI with a rejection threshold of 7 or higher for cluster data with a large number of exposures per filter. This option allows us to remove slow-moving asteroids which are difficult to identify in individual images. For MS0451.6–0305, we were able to reuse coadds that were produced and analysed in Schirmer et al. (2010). In the case of RXCJ1347, half of the archival Suprime-Cam data were observed with a field-of-view rotated by 90° . Since inclusion of these images resulted in a significantly poorer quality of the astrometric solution, we did not consider this data further.

2.1 Photometric calibration

The indirect calibration of the absolute photometric zero point is based on observations of standard fields (Stetson 2000) during photometric nights, where the atmospheric extinction is assumed to be stable over night. In order to calibrate data sets obtained under

Table 1. Cluster data sets: For the clusters analysed in this study, we list the redshift z_{NED} as quoted in NED, the filters (the lensing band is denoted by \star), exposure time, number N of coadded exposures, and seeing conditions in the lensing band. In the last column, ‘WFI’ is the Wide-Field Imager at the 2.2 m MPG/ESO telescope, while ‘SUP’ denotes Suprime–Cam at the Subaru telescope. The subscript ‘S’ is used to distinguish between Suprime–Cam and WFI-based data in case of mixed data sets.

| Cluster | z | Filter | Time [s] | N | Seeing ["] | Instrument |
|--------------------|-------|-----------------------|----------|-----|------------|------------|
| A2744 | 0.307 | B, V, R^\star | 20997 | 40 | 0.87 | WFI |
| RXCJ0019.0–2026 | 0.277 | B, V, R^\star | 14918 | 30 | 0.82 | WFI |
| A2813 | 0.292 | B, V, R^\star | 13497 | 26 | 0.89 | WFI |
| A209 | 0.206 | B, R^\star, Z | 2400 | 10 | 0.58 | SUP |
| XLSSC 006 | 0.429 | $V, R_{C,S}^\star, Z$ | 1800 | 4 | 0.69 | WFI,SUP |
| RXCJ0232.2–4420 | 0.284 | B, V, R^\star | 13398 | 25 | 0.77 | WFI |
| RXCJ0245.4–5302 | 0.302 | B, V, R^\star | 14697 | 31 | 0.92 | WFI |
| A383 | 0.187 | B, V, R_C^\star | 5400 | 18 | 0.69 | SUP |
| RXCJ0437.1 + 0043 | 0.284 | B, V, R^\star | 18097 | 33 | 0.82 | WFI |
| MS0451.6–0305 | 0.539 | B, R_C^\star, Z | 11400 | 26 | 0.83 | SUP |
| A520 | 0.199 | V, R, I^\star | 3000 | 13 | 0.57 | SUP |
| RXCJ0516.6–5430 | 0.295 | B, V, R^\star | 14548 | 25 | 0.91 | WFI |
| RXCJ0528.9–3927 | 0.284 | B, V, R^\star | 20776 | 48 | 0.85 | WFI |
| RXCJ0532.9–3701 | 0.275 | B, V, R^\star | 13998 | 28 | 0.73 | WFI |
| A3404 | 0.167 | B, V, R^\star | 10078 | 28 | 0.92 | WFI |
| Bullet | 0.297 | B, V, R^\star | 16447 | 35 | 0.77 | WFI |
| A907 | 0.153 | B, V, R_C^\star | 4800 | 16 | 0.53 | SUP |
| | 0.153 | B, V, R^\star | 8638 | 24 | 0.80 | WFI |
| RXCJ1023.6 + 0411 | 0.280 | B, V, I^\star | 2160 | 9 | 0.62 | WFI,SUP |
| MS1054.4–0321 | 0.831 | V, R^\star, Z | 19547 | 33 | 0.73 | WFI,SUP |
| MACSJ1115.8 + 0129 | 0.348 | B, V, R_s^\star | 1200 | 5 | 0.63 | SUP |
| | 0.350 | B, V, R^\star | 14497 | 29 | 0.75 | WFI |
| A1300 | 0.308 | B, V, R^\star | 16997 | 34 | 0.73 | WFI |
| RXCJ1135.6–2019 | 0.305 | B, V, R^\star | 14998 | 30 | 0.77 | WFI |
| RXCJ1206.2–0848 | 0.441 | B, V, I_C^\star | 1080 | 3 | 0.73 | SUP |
| MACSJ1311.0–0311 | 0.494 | B, V, R_C^\star | 1080 | 6 | 0.62 | WFI,SUP |
| A1689 | 0.183 | B, R_C^\star, I | 7984 | 29 | 0.69 | SUP |
| RXJ1347–1145 | 0.451 | V, R, Z^\star | 2700 | 11 | 0.54 | SUP |
| | 0.451 | B, V, R^\star | 16297 | 28 | 0.85 | WFI |
| MACSJ1359.2–1929 | 0.447 | B, V, R^\star | 15032 | 31 | 0.84 | WFI |
| A1835 | 0.253 | B, V, I^\star | 1440 | 6 | 0.90 | WFI,SUP |
| RXJ1504 | 0.215 | B, V_s^\star, R | 2640 | 11 | 0.78 | WFI,SUP |
| A2163 | 0.203 | V, R_C, I^\star | 4500 | 15 | 0.68 | SUP |
| A2204 | 0.152 | V, R_s, I^\star | 1680 | 7 | 0.67 | SUP |
| RXCJ2014.8–2430 | 0.160 | B, V, R^\star | 14277 | 27 | 0.80 | WFI |
| RXCJ2151.0–0736 | 0.284 | B, V, R^\star | 14998 | 30 | 0.79 | WFI |
| A2390 | 0.228 | B, R_C^\star, Z | 3700 | 11 | 0.57 | SUP |
| MACSJ2214.9–1359 | 0.483 | V, R_C^\star, I_C | 1200 | 5 | 0.53 | SUP |
| MACSJ2243.3–0935 | 0.447 | B, V^\star, Z | 1080 | 3 | 0.75 | SUP |
| RXCJ2248.7–4431 | 0.348 | B, V, R^\star | 32995 | 55 | 0.80 | WFI |
| A2537 | 0.297 | V, R_C^\star, I | 2400 | 5 | 0.69 | SUP |
| RXCJ2337.6 + 0016 | 0.278 | B, V, R_C^\star | 720 | 3 | 0.62 | SUP |

unknown or non-photometric conditions and to ensure a highly accurate colour calibration, we performed a two-step calibration for the WFI data where the last step was also applied to the Suprime–Cam data.

In the first step, we perform a WFI-internal colour calibration, by matching the colours of the stellar locus of each cluster field with that of a field observed under photometric conditions. This can be done by simply shifting the position of the main sequence in colour–colour–space without the need of rotation or stretching. We then use the stars of the matched fields which are brighter than $R = 21.5$ mag as a reference main sequence for the second step.

The second step is a stellar locus regression (SLR) comparable to High et al. (2009) in order to perform a colour transformation

between the WFI or Suprime–Cam bands and the related bands in the COSMOS photo- z catalogue (Ilbert et al. 2009). We measure the scaling, rotation, and shifting terms by matching the prominent features of the stellar locus of the calibrated WFI sequence with that of the COSMOS field. The resulting excellent agreement can be seen in Fig. 1.

Calibrating the colours against COSMOS makes a background selection possible which is relatively independent of the instrument used because the colours are converted to the same reference system. High et al. (2009) also showed that applying an SLR can also account for galactic extinction if the reference locus is calibrated for that. This is the case for the COSMOS photo- z catalogue. We, therefore, do not apply any additional extinction correction. The

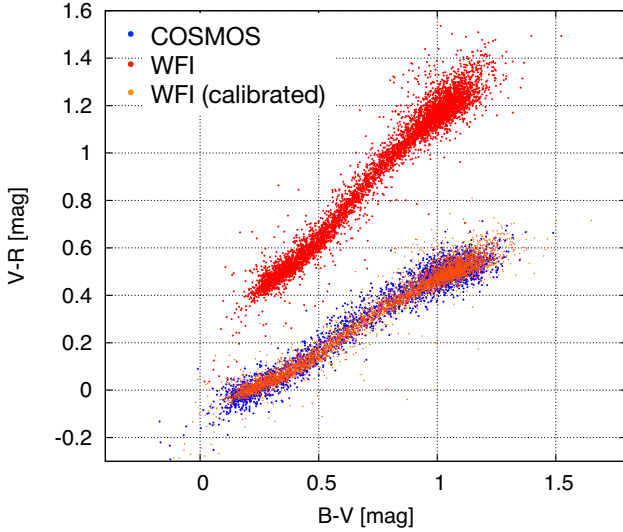


Figure 1. Photometric calibration by stellar locus regression (SLR). Blue symbols show stars $R < 22$ mag in the COSMOS field (using the B , V , R_C bands). Red symbols denote stars $R < 22$ observed with WFI (using the B , V , R bands). Orange symbols denote the same WFI stars after SLR calibration.

SLR also needs to be applied to Suprime-Cam data. However, as the COSMOS photo- z catalogue is based on Suprime-Cam observations, the colour calibration is in most cases straightforward. Since we calibrate the colours against the same colour system, we use from now on just the shortcuts B , V , and R band irrespective of whether it is, e.g. the $V-89$ (WFI) or the $W-J-V$ (Suprime-Cam) band.

To obtain the absolute zero points, we match our catalogue with the AllWISE catalogue (Cutri & et al. 2014) and perform a stellar locus match in the $V-R$ versus $R-[W1]$ plane, keeping the $V-R$ colour fixed to the values from the previous calibration. AllWISE increases the depth of the Wide-Field Infrared Survey explorer [WISE, Wright et al. (2010)] catalogues. Here, $[W1]$ denotes the $3.4 \mu\text{m}$ WISE passband.

By matching the $V-R$ versus $R-[W1]$ locus to that of our reference catalogue, we ensure that the overall zero point matches the photometric system of the reference catalogue. Using $30 \text{ arcmin} \times 30 \text{ arcmin}$ subfields of the reference catalogue and applying the same calibration method yields a scatter in the absolute zero points of ~ 0.05 mag. Since we expect correlations between the different subfields, the scatter has to be taken as a lower limit. We investigate the impact of the zero point scatter on the derived lensing properties in Section 5.3. Repetition tests show that we are able to recover the relative zero points to an accuracy of 0.013 mag.

3 WEAK GRAVITATIONAL LENSING BY GALAXY CLUSTERS

3.1 Lensing theory

This section briefly summarizes the basic theory of weak gravitational lensing by galaxy clusters used in this paper. For a more complete introduction to weak gravitation lensing, we refer the interested reader to Bartelmann & Schneider (2001) and Schneider (2006).

The mapping of a gravitational lens between true position $\vec{\alpha}$ and observed position $\vec{\theta}$ can be described by the Jacobian Matrix

$$\mathcal{A}(\vec{\theta}) = \frac{\partial \vec{\alpha}}{\partial \vec{\theta}} = \left(\delta_{ij} - \frac{\partial^2 \psi(\vec{\theta})}{\partial \theta_i \partial \theta_j} \right). \quad (1)$$

Here, ψ is the lensing potential, which is related to the surface mass density κ as

$$\psi(\vec{\theta}) = \frac{1}{\pi} \int \kappa(\vec{\theta}') \ln |\vec{\theta} - \vec{\theta}'| d\vec{\theta}'. \quad (2)$$

The surface mass density κ is generally expressed in units of the critical surface density Σ_{crit} , which is defined as

$$\Sigma_{\text{crit}} = \frac{c^2}{4\pi G D_d} \frac{D_s}{D_{ds}}, \quad (3)$$

where c is the speed of light, G the gravitational constant, and D_d , D_s , D_{ds} are the angular diameter distances between the observer and deflector (lens), the observer and source, and between the deflector and source. The second term of this equation describes the strength of the light deflection in dependency of the source distance and is usually referred to as angular diameter ratio $\beta = D_{ds}/D_s$.

Using the shear $\gamma_1 = (\psi_{,11} - \psi_{,22})/2$, $\gamma_2 = \psi_{,12}$, and convergence $\kappa = (\psi_{,11} + \psi_{,22})/2$, we can rewrite the Jacobian matrix and get

$$\mathcal{A} = \begin{pmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 \\ -\gamma_2 & 1 - \kappa + \gamma_1 \end{pmatrix}. \quad (4)$$

The actual observable in the weak lensing shear measurements is not the shear but the reduced shear, which is given as

$$g(\theta) = \frac{\gamma(\theta)}{1 - \kappa(\theta)}. \quad (5)$$

Using the reduced shear, the lens mapping can be expressed as

$$\mathcal{A}(\theta) = (1 - \kappa(\theta)) \begin{pmatrix} 1 - g_1(\theta) & -g_2(\theta) \\ -g_2(\theta) & 1 + g_1(\theta) \end{pmatrix}. \quad (6)$$

In the weak lensing regime with κ , $|\gamma| \ll 1$, $\det \mathcal{A}(\theta) > 0$, we can decompose the image distortions into two different effects: the image shape distortion and the (de-)magnification. The reduced shear describes the distortion of the source image caused by the gravitational lens. In the weak lensing case, a circular source image gets distorted to an ellipse with ellipticity $\varepsilon = g$.

The magnification effect which can be described by the inverse Jacobian determinant,

$$\mu = \frac{1}{\det \mathcal{A}} = \frac{1}{(1 - \kappa)^2 - |\gamma|^2} = \frac{1}{(1 - \kappa)^2 (1 - |g|^2)}. \quad (7)$$

increases the size of the galaxy image by the factor μ leaving the flux density conserved.

Since the intrinsic size and ellipticity of the individual source are unknown, magnification and shear can only be measured over a sample of sources where the average intrinsic property can be estimated. In the case of shear measurements, the intrinsic ellipticities of a sufficiently high number of background galaxies are averaging to zero, and thus the observed image ellipticities are then a direct measure of g .

3.2 The angular diameter distance ratio

The lensing-induced ellipticity ε scales with the angular diameter distance ratio β because κ and γ do so. To estimate β for each of the faint source galaxy, photometric redshifts (photo- z) are needed.

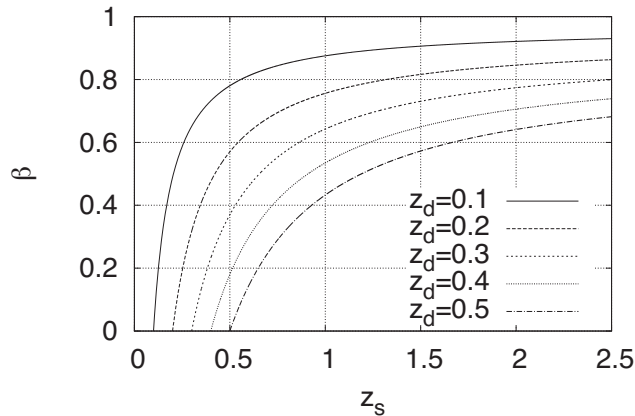


Figure 2. Angular diameter distance ratio β as a function of the source redshift z_s for different cluster redshifts z_d .

Most authors that are using three filters do not attempt to derive individual redshift estimates (Medezinski et al. 2010; Hoekstra et al. 2012; von der Linden et al. 2014) and use polygonal-shaped regions in colour–colour space to exclude cluster members. Empirically derived photo- z ’s of individual galaxies using three filters is rather rare in cluster-weak lensing studies but was previously used in smaller studies by Gruen et al. (2014) and Rehmman et al. (2019).

The standard approach for three-filter observations is to estimate a single-mean angular diameter distance ratio $\langle\beta\rangle$. This value is obtained by investigating the redshift distribution of a reference photo- z catalogue by applying similar colour, size, and flux cuts as in the lensing observations. This approach can be called *source sheet approximation*, since it assigns one single distance estimate to all galaxies.

Fig. 2 shows the dependency of β on that single-source redshift z_s for different cluster redshifts z_d . For clusters at low redshifts and deep observational data, most of the observed galaxies will lie on the flat part of the β curve. Therefore, the scatter in β is small even for broad-source redshift distributions, and the noise introduced by the source sheet approximation is negligible. At higher redshifts or shallower data, most of the source will lie on the steep part of the β curve, introducing an additional source of noise to the shear estimate if only an average $\langle\beta\rangle$ is assumed.

The source sheet approximation is prone to biases, which are introduced by the systematic changes of the redshift distribution that correlate with the mass distribution in a cluster field. First, such a systematic change can be introduced by the magnification effect [equation (7)] which is strongly correlated with the mass distribution.

A second source of such correlated variation of the redshift distribution can be introduced by targeted observations of clusters. Due to vignetting, the noise properties of the image change systematically from the centre to the outskirts. This again affects the probability of a source to be detected. If centred on a cluster, this effect would follow the overall mass profile of the cluster and therefore bias the result.

A third source of bias, related to the lack of precise distance estimates, is the contamination by cluster galaxies. Since the distribution of member galaxies correlates with the (projected) mass distribution while the cluster members systematically change the redshift distribution compared to the reference field, their

contamination of the lensing signal has to be minimized or properly accounted for. In particular, uncorrected contamination by cluster members systematically affects the observed shear profile.

While the first two effects tend to boost the shear signal towards the centre, yielding more concentrated mass distributions than the true one when modelling the shear profile (Section 3.4), the last effect suppresses the shear signal towards the centre, resulting in an underestimate of the concentration parameter. Low concentration parameters can therefore be a hint of significant contamination by cluster galaxies.

3.3 PSF correction and shape catalogues

Besides the challenges related to the distance estimates of the lensed sources, accurate shape measurements of these galaxies are of critical importance for unbiased mass estimates. Important in this context is that the instrumental effects on the observed ellipticities are accounted for and that the measured ellipticity is an unbiased estimate of the true one.

Both instruments used, Suprime-Cam as well as WFI, are known for their weak lensing capability for more than a decade (Clowe & Schneider 2002; Miyazaki et al. 2002). Their smooth variation of the PSF anisotropy can be modelled by a low-order ($3 \leq d_{\text{ani}} \leq 5$) polynomial in image coordinates. Therefore, they are well suited for our purpose.

The software and measurement scheme applied to the co-added images in order to get positions, PSF-corrected ellipticities and photometric data for the source galaxies is mostly identical to those presented in Israel et al. (2010, 2012). We, therefore, briefly summarize the methods in order to show the basic steps of the data processing and refer the interested reader to the aforementioned papers for a more detailed discussion.

The photometry was performed using SExtractor in dual-image mode on seeing-equalized images, using the unconvolved lensing band as detection image. This ensures good-quality galaxy colours and proper total flux estimates in the lensing band. For the lensing measurement, we apply the ‘TS’ shear measurement pipeline (Heymans et al. 2006; Schrabback et al. 2007; Hartlap et al. 2009), an implementation of the KSB + algorithm (Kaiser, Squires & Broadhurst 1995; Erben et al. 2001). The PSF anisotropy is traced by measuring the brightness distribution of sources identified as unsaturated stars in the magnitude versus half-light radius 9 plots.

For the clusters observed with WFI, we use the R band for the shape analysis since it is usually the deepest and has the best seeing out of the three bands. In cases where we have to rely on archival data, we choose the filter which offers the best compromise in terms of seeing, depth, and number of images. The latter factor becomes important when the number gets small. Since we apply our PSF correction on the coadded images, we rely on image distortions being smooth over the whole field. This assumption can be violated at the position of chip gaps if the observation conditions have changed between the exposures. In some cases such as RXC 1504, we had to combine the photometry data of WFI with the shear measurements of Suprime-Cam since the WFI R band data were split into two different pointings making it difficult to correct for the PSF anisotropy. The residual PSF anisotropy after correction has a dispersion of $0.004 \leq \sigma \leq 0.011$ in the lensing image and a nearly vanishing mean value typically two orders of magnitude smaller than the dispersion.

We keep sources in our lensing catalogue which are fainter than the brightest unsaturated point sources and whose half light radius

are larger than that of stars $\vartheta_{\text{gal}} > \vartheta_{\text{max}}^*$. Since the estimate of the half light radius gets more and more noisy for fainter sources, we also include faint sources with $\vartheta_{\text{ana}} < \vartheta_{\text{gal}} \leq \vartheta_{\text{max}}^*$ for $R > 23.5$. For sources in the same size range but between $R = 23.5$ and the magnitude $R_{\text{max}}^* \sim 22$, where the stellar locus in the ϑ vs. R distribution becomes indistinguishable from the cloud of galaxies, we exclude all sources which have more than 10 stars in the colour-colour region that is created by the source colours and its errors. As a reference, we consider stars in the COSMOS photo- z catalogue.

The choice of the magnitude limit is motivated by the assumption of an absolute magnitude of $M_V = 17$ mag (Henry 2004) for the faintest main sequence stars, a thin galactic disc of scale height of 240 pc (Jurić et al. 2008) and typical colour of $V - R = 1.2$. The limit of $R = 23.5$ therefore accounts for the majority of stars within the galactic disc for galaxy clusters at galactic latitudes of 40° or higher.

3.4 Shear profile modelling and cluster masses

In order to obtain cluster masses from our shear measurements, we are again following a similar approach as described in Israel et al. (2010) and model the tangential ellipticity profile $\varepsilon_t(\theta)$ of a cluster with the reduced shear profile $g(\theta, \Sigma_{\text{crit}, i}; r_{200}, c_{200})$ (Bartelmann 1996; Wright & Brainerd 2000) of an NFW (Navarro, Frenk & White 1995, 1996, 1997) density profile. In contrast to Israel et al. (2010), we do not assume a source sheet with common Σ_{crit} . Instead we use individual $\Sigma_{\text{crit}, i}(\beta_i)$ based on the individually estimated β_i for each galaxy i . We derive the best-fitting profile parameters r_{200} and c_{200} by minimizing the merit function

$$\chi^2 = \sum_{i=1}^N \frac{|g_i(\theta_i, \Sigma_{\text{crit}, i}; r_{200}, c_{\text{NFW}}) - \tilde{\varepsilon}_{t,i}(\theta_i)|^2}{\tilde{\sigma}_i^2 \left(1 - |g_i(\theta_i, \Sigma_{\text{crit}, i}; r_{200}, c_{\text{NFW}})|^2\right)}, \quad (8)$$

which is calculated on a regular grid in the r_{200} – c_{200} plane. Here, r_{200} corresponds to the radius within which the enclosed mass density equals 200 times the critical density $\rho_c(z_d)$ at cluster redshift z_d . The concentration parameter cannot be well constrained with our weak lensing data. For this, we therefore adopt a prior from the mass–concentration relation given in (Bhattacharya et al. 2013) for the final mass estimate. A detailed discussion on the concentration parameter obtained with and without prior is presented in Section 6.1.2. The modified tangential ellipticity $\tilde{\varepsilon}_{t,i}$ is the measured tangential ellipticity multiplied by a global shear calibration factor $f_0 = 1.08$, identical to that used in Israel et al. (2010). The error $\tilde{\sigma}_i$ scales as $\tilde{\sigma}_i = f_0 \sigma_e / \sqrt{2}$, where σ_e is the dispersion of the measured ellipticities.

The index i runs over all lensing catalogue galaxies with separations within the fitting range $\theta_{\text{min}} \leq \theta \leq \theta_{\text{max}}$ from the assumed cluster centre. The denominator of equation (8) accounts for the dependence of the noise on $g_i(\theta_i)$ itself (Schneider, King & Erben 2000). After estimation of r_{200} , the cluster mass within that radius can be calculated as follows

$$M_{200} = 200 \frac{4\pi}{3} \rho_c(z_d) r_{200}^3. \quad (9)$$

Calculating χ^2 on a grid, some areas of the explored parameter space can result in a model which suggests $g_i > 0.5$ at $\theta_i > \theta_{\text{min}}$. In those cases, we change θ_{min} to the value which is fulfilling $g_i(\theta_{\text{min}}) = 0.5$. The impact of this additional constrain is typically negligible and mainly ensures robustness of the results when exploring more exotic areas of the parameter space. It is therefore only needed for the case where the concentration is free to vary. The application of the prior

from the mass–concentration relation further ensures a reasonable parameter space. We centred our profile fits to the position of the BCG and list θ_{min} and θ_{max} in Table 2.

3.5 Weak lensing convergence maps

Besides the accurate measurement of the total mass, the mass distribution of the galaxy clusters can also be of interest. Especially, in case of studies of individual clusters, the mass distribution can give insights into the dynamical nature of a cluster.

For the convergence reconstructions, we are using the finite-field inversion algorithm (Seitz & Schneider 1996, 2001). The mass sheet degeneracy¹ is broken by using the assumption that the mean convergence vanishes along the edge of the images. A violation of this assumption would lead to a wrong normalization but would not affect the general shape of the cluster mass distribution. The lensing convergence or surface mass density κ is calculated on a regular grid with a grid size of ~ 5 arcsec. On each grid point, we use an aperture radius of $\theta_A = 1.5'$ where the input shear field is smoothed by a truncated Gaussian filter with an FWHM of $0.555 \theta_A$ dropping to zero at θ_A . By using the assumption of a linear scaling of κ with β , we rescale the observed ellipticities to the average β . This assumption produces a bias at higher convergence but accounts for changes in image depths and contamination. For RXC1347, we corrected the contour levels of the WFI map with respect to the average β found in the Suprime–Cam data.

4 BACKGROUND SELECTION

As stressed in the previous section, distance estimates of the observed galaxies are important to avoid biases and to minimize the number of cluster members contaminating the lensing catalogue. Unaccounted contamination will cause a dilution of the signal and result in a systematic bias of the mass estimate. While this might be sub-dominant compared to statistical errors for a single cluster, this systematic effect becomes important for the investigation of large cluster samples.

Current background selections based on two colours typically exclude certain regions in colour–colour space (cc-space). One of the most thorough studies of the cc-space for an optimized weak lensing background selection was made by Medezinski et al. (2010). There, the regions were selected by their mean distance with respect to the cluster centre and the number density in colour–colour-space. This method allows to find easily the location of the red sequence galaxies for relaxed clusters but not the bluer cluster and field galaxies which are less or not concentrated at the cluster centre. These galaxies were excluded by introducing a second region, based on overdensity in the cc-plane and the lack of a significant weak lensing signal. These selection polygons were then justified by evolutionary colour tracks and the application of the colour cuts on a photo- z catalogue. However, Ziparo et al. (2016) developed a photometric method for selecting blue galaxies for their inclusion into lensing catalogues.

Related to the background selection is also the estimate of β for individual galaxies, or, using the source-sheet approximation, the mean lensing depth $\langle \beta \rangle$. Colour cut methods usually simply apply the polygon selection to a reference photo- z catalogue to derive $\langle \beta \rangle$ and thus do not account for remaining differences between

¹The observed reduced shear is invariant under convergence transformations of the form $\kappa \rightarrow \kappa' = \lambda \kappa + (1 - \lambda)$ for a scalar constant λ .

Table 2. Lensing results. Columns (2)–(5) show detection–optimizing distance ratio cuts β_{cut} , the lower purity cuts p_{cut} (4.2), the mean distance ratios $\langle\beta\rangle$, and mean purity $\langle p_g \rangle$, of the background galaxy sample. In Columns (6)–(8), we give the radii r_{200} , concentration parameters c_{200} , and cluster masses M_{200} obtained from the NFW fits to the shear profile (3.4). Assuming these profiles to be correct, the corresponding $\Delta = 500$ values were computed [Columns (8)–(10)]. The radial range of these fits is defined between the separations θ_{min} and θ_{max} in Columns (11) and (12). (S): Results based on Suprime–Cam. (W): Results based on WFI.

| Cluster | β_{cut} | p_{cut} | $\langle\beta_g\rangle$ | $\langle p_g \rangle$ | R_{200} | c_{200} | M_{200} | R_{500} | c_{500} | M_{500} | Θ_{min} | Θ_{max} |
|-----------------------------------|----------------------|------------------|-------------------------|-----------------------|------------------------|------------------------|---------------------------|------------------------|------------------------|---------------------------|-----------------------|-----------------------|
| | | | | | [Mpc] | | [$10^{14} M_{\odot}$] | [Mpc] | | [$10^{14} M_{\odot}$] | [arcsec] | [arcmin] |
| A2744 | 0.47 | 0.5 | 0.55 | 0.91 | $2.32^{+0.12}_{-0.12}$ | $3.30^{+1.10}_{-1.10}$ | $17.47^{+3.02}_{-2.71}$ | $1.41^{+0.08}_{-0.08}$ | $2.12^{+0.71}_{-0.71}$ | $11.55^{+2.00}_{-1.79}$ | 120 | 1100 |
| RXCJ0019.0–2026 | 0.36 | 0.4 | 0.54 | 0.92 | $2.05^{+0.12}_{-0.13}$ | $3.45^{+1.15}_{-1.15}$ | $11.51^{+2.28}_{-2.17}$ | $1.24^{+0.08}_{-0.08}$ | $2.22^{+0.74}_{-0.74}$ | $7.70^{+1.53}_{-1.45}$ | 30 | 1000 |
| A2813 | 0.33 | 0.3 | 0.53 | 0.9 | $2.10^{+0.13}_{-0.13}$ | $3.45^{+1.15}_{-1.15}$ | $12.41^{+2.62}_{-2.30}$ | $1.27^{+0.08}_{-0.08}$ | $2.22^{+0.74}_{-0.74}$ | $8.30^{+1.75}_{-1.54}$ | 40 | 900 |
| A209 | 0.54 | 0.8 | 0.7 | 0.96 | $2.18^{+0.09}_{-0.09}$ | $3.55^{+1.18}_{-1.18}$ | $13.49^{+1.82}_{-1.67}$ | $1.35^{+0.06}_{-0.06}$ | $2.29^{+0.76}_{-0.76}$ | $9.08^{+1.22}_{-1.12}$ | 90 | 1000 |
| XLSSC 006 | 0.3 | 0.6 | 0.45 | 0.85 | $1.71^{+0.13}_{-0.15}$ | $3.35^{+1.12}_{-1.12}$ | $7.49^{+2.00}_{-1.94}$ | $1.02^{+0.08}_{-0.10}$ | $2.15^{+0.72}_{-0.72}$ | $4.97^{+1.33}_{-1.29}$ | 30 | 850 |
| RXCJ0232.2–4420 | 0.4 | 0.5 | 0.52 | 0.93 | $1.87^{+0.19}_{-0.21}$ | $3.60^{+1.20}_{-1.20}$ | $7.59^{+2.88}_{-2.51}$ | $1.09^{+0.12}_{-0.14}$ | $2.33^{+0.78}_{-0.78}$ | $5.13^{+1.94}_{-1.69}$ | 50 | 800 |
| RXCJ0245.4–5302 | 0.36 | 0.8 | 0.51 | 0.93 | $1.64^{+0.18}_{-0.20}$ | $3.70^{+1.23}_{-1.23}$ | $5.11^{+2.13}_{-1.82}$ | $0.95^{+0.12}_{-0.13}$ | $2.40^{+0.80}_{-0.80}$ | $3.47^{+1.45}_{-1.24}$ | 15 | 1000 |
| A383 | 0.48 | 0.8 | 0.65 | 0.94 | $1.92^{+0.11}_{-0.13}$ | $3.70^{+1.23}_{-1.23}$ | $8.61^{+1.67}_{-1.73}$ | $1.17^{+0.07}_{-0.08}$ | $2.40^{+0.80}_{-0.80}$ | $5.86^{+1.13}_{-1.17}$ | 40 | 900 |
| RXCJ0437.1 + 0043 | 0.25 | 0.5 | 0.51 | 0.91 | $2.12^{+0.16}_{-0.18}$ | $3.45^{+1.15}_{-1.15}$ | $12.12^{+3.22}_{-3.04}$ | $1.26^{+0.10}_{-0.12}$ | $2.22^{+0.74}_{-0.74}$ | $8.10^{+2.15}_{-2.03}$ | 10 | 900 |
| MS0451.6–0305 | 0.36 | 0.6 | 0.4 | 0.91 | $1.79^{+0.17}_{-0.19}$ | $3.15^{+1.05}_{-1.05}$ | $9.31^{+3.25}_{-2.91}$ | $1.04^{+0.11}_{-0.12}$ | $2.01^{+0.67}_{-0.67}$ | $6.08^{+2.12}_{-1.90}$ | 30 | 900 |
| A520 | 0.43 | 0.7 | 0.66 | 0.94 | $1.86^{+0.10}_{-0.11}$ | $3.70^{+1.23}_{-1.23}$ | $8.02^{+1.45}_{-1.41}$ | $1.14^{+0.06}_{-0.07}$ | $2.40^{+0.80}_{-0.80}$ | $5.45^{+0.98}_{-0.96}$ | 5 | 900 |
| RXCJ0516.6–5430 | 0.28 | 0.6 | 0.5 | 0.91 | $2.13^{+0.15}_{-0.17}$ | $3.40^{+1.13}_{-1.13}$ | $12.64^{+3.10}_{-2.99}$ | $1.27^{+0.10}_{-0.11}$ | $2.19^{+0.73}_{-0.73}$ | $8.42^{+2.06}_{-1.99}$ | 60 | 1100 |
| RXCJ0528.9–3927 | 0.39 | 0.5 | 0.54 | 0.92 | $1.74^{+0.15}_{-0.17}$ | $3.65^{+1.22}_{-1.22}$ | $6.47^{+2.01}_{-1.86}$ | $1.03^{+0.10}_{-0.11}$ | $2.36^{+0.79}_{-0.79}$ | $4.38^{+1.36}_{-1.26}$ | 20 | 1000 |
| RXCJ0532.9–3701 | 0.34 | 0.6 | 0.56 | 0.94 | $1.98^{+0.13}_{-0.13}$ | $3.50^{+1.17}_{-1.17}$ | $10.08^{+2.28}_{-1.98}$ | $1.19^{+0.08}_{-0.08}$ | $2.26^{+0.75}_{-0.75}$ | $6.76^{+1.53}_{-1.33}$ | 45 | 1000 |
| A3404 | 0.54 | 0.6 | 0.69 | 0.97 | $2.23^{+0.17}_{-0.17}$ | $3.65^{+1.22}_{-1.22}$ | $12.40^{+3.33}_{-2.82}$ | $1.33^{+0.11}_{-0.11}$ | $2.36^{+0.79}_{-0.79}$ | $8.40^{+2.26}_{-1.91}$ | 60 | 1000 |
| Bullet | 0.31 | 0.5 | 0.5 | 0.9 | $1.97^{+0.18}_{-0.18}$ | $3.50^{+1.17}_{-1.17}$ | $9.34^{+3.11}_{-2.54}$ | $1.15^{+0.12}_{-0.12}$ | $2.26^{+0.75}_{-0.75}$ | $6.27^{+2.09}_{-1.71}$ | 10 | 1100 |
| A907 ^(W) | 0.63 | 0.7 | 0.73 | 0.98 | $1.62^{+0.17}_{-0.18}$ | $4.00^{+1.33}_{-1.33}$ | $4.26^{+1.68}_{-1.40}$ | $0.94^{+0.11}_{-0.12}$ | $2.61^{+0.87}_{-0.87}$ | $2.95^{+1.16}_{-0.97}$ | 30 | 1000 |
| A907 ^(S) | 0.63 | 0.8 | 0.75 | 0.97 | $1.66^{+0.14}_{-0.14}$ | $3.95^{+1.32}_{-1.32}$ | $4.91^{+1.48}_{-1.23}$ | $0.99^{+0.09}_{-0.09}$ | $2.57^{+0.86}_{-0.86}$ | $3.39^{+1.02}_{-0.85}$ | 60 | 900 |
| RXCJ1023.6 + 0411 | 0.4 | 0.6 | 0.56 | 0.9 | $2.06^{+0.09}_{-0.10}$ | $3.45^{+1.15}_{-1.15}$ | $12.38^{+1.78}_{-1.79}$ | $1.27^{+0.06}_{-0.06}$ | $2.22^{+0.74}_{-0.74}$ | $8.28^{+1.19}_{-1.20}$ | 20 | 900 |
| MS1054.4–0321 | 0.15 | 0.3 | 0.21 | 0.78 | $2.48^{+0.52}_{-0.66}$ | $2.55^{+0.85}_{-0.85}$ | $23.03^{+23.63}_{-16.31}$ | $1.23^{+0.33}_{-0.41}$ | $1.60^{+0.53}_{-0.53}$ | $14.20^{+14.57}_{-10.06}$ | 100 | 660 |
| MACSJ1115.8 + 0129 ^(W) | 0.37 | 0.6 | 0.47 | 0.89 | $1.73^{+0.20}_{-0.22}$ | $3.55^{+1.18}_{-1.18}$ | $6.24^{+2.78}_{-2.32}$ | $0.99^{+0.13}_{-0.14}$ | $2.29^{+0.76}_{-0.76}$ | $4.20^{+1.87}_{-1.56}$ | 40 | 1000 |
| MACSJ1115.8 + 0129 ^(S) | 0.33 | 0.5 | 0.48 | 0.9 | $1.85^{+0.18}_{-0.19}$ | $3.45^{+1.15}_{-1.15}$ | $8.12^{+2.92}_{-2.47}$ | $1.08^{+0.12}_{-0.12}$ | $2.22^{+0.74}_{-0.74}$ | $5.43^{+1.95}_{-1.65}$ | 30 | 900 |
| A1300 | 0.34 | 0.5 | 0.5 | 0.9 | $1.90^{+0.16}_{-0.18}$ | $3.50^{+1.17}_{-1.17}$ | $8.68^{+2.62}_{-2.42}$ | $1.12^{+0.10}_{-0.12}$ | $2.26^{+0.75}_{-0.75}$ | $5.82^{+1.76}_{-1.63}$ | 90 | 1000 |
| RXCJ1135.6–2019 | 0.37 | 0.5 | 0.53 | 0.93 | $1.73^{+0.14}_{-0.16}$ | $3.60^{+1.20}_{-1.20}$ | $6.62^{+1.91}_{-1.80}$ | $1.03^{+0.09}_{-0.10}$ | $2.33^{+0.78}_{-0.78}$ | $4.47^{+1.29}_{-1.22}$ | 5 | 1000 |
| RXCJ1206.2–0848 | 0.38 | 0.5 | 0.45 | 0.96 | $2.09^{+0.19}_{-0.22}$ | $3.20^{+1.07}_{-1.07}$ | $13.21^{+4.37}_{-4.08}$ | $1.22^{+0.12}_{-0.14}$ | $2.05^{+0.68}_{-0.68}$ | $8.67^{+2.87}_{-2.68}$ | 100 | 800 |
| MACSJ1311.0–0311 | 0.23 | 0.2 | 0.37 | 0.82 | $1.88^{+0.15}_{-0.17}$ | $3.20^{+1.07}_{-1.07}$ | $10.61^{+3.01}_{-2.83}$ | $1.11^{+0.10}_{-0.11}$ | $2.05^{+0.68}_{-0.68}$ | $6.96^{+1.97}_{-1.86}$ | 10 | 900 |
| A1689 | 0.46 | 0.5 | 0.65 | 0.91 | $2.85^{+0.07}_{-0.07}$ | $3.35^{+1.12}_{-1.12}$ | $30.98^{+2.40}_{-2.28}$ | $1.79^{+0.04}_{-0.04}$ | $2.15^{+0.72}_{-0.72}$ | $20.56^{+1.59}_{-1.51}$ | 50 | 1200 |
| RXJ1347–1145 ^(W) | 0.2 | 0.4 | 0.35 | 0.87 | $2.18^{+0.19}_{-0.20}$ | $3.15^{+1.05}_{-1.05}$ | $15.35^{+4.83}_{-4.18}$ | $1.27^{+0.12}_{-0.13}$ | $2.01^{+0.67}_{-0.67}$ | $10.03^{+3.16}_{-2.73}$ | 40 | 1000 |
| RXJ1347–1145 ^(S) | 0.17 | 0.4 | 0.38 | 0.87 | $2.38^{+0.15}_{-0.17}$ | $3.05^{+1.02}_{-1.02}$ | $21.60^{+4.66}_{-4.57}$ | $1.42^{+0.10}_{-0.11}$ | $1.94^{+0.65}_{-0.65}$ | $14.00^{+3.02}_{-2.96}$ | 30 | 1000 |
| MACSJ1359.2–1929 | 0.24 | 0.3 | 0.37 | 0.87 | $1.70^{+0.22}_{-0.26}$ | $3.40^{+1.13}_{-1.13}$ | $6.28^{+3.24}_{-2.76}$ | $0.95^{+0.14}_{-0.17}$ | $2.19^{+0.73}_{-0.73}$ | $4.19^{+2.16}_{-1.84}$ | 20 | 900 |
| A1835 | 0.44 | 0.6 | 0.6 | 0.96 | $2.51^{+0.14}_{-0.15}$ | $3.35^{+1.12}_{-1.12}$ | $20.70^{+3.89}_{-3.69}$ | $1.52^{+0.09}_{-0.10}$ | $2.15^{+0.72}_{-0.72}$ | $13.74^{+2.58}_{-2.45}$ | 60 | 900 |
| RXJ1504 | 0.49 | 0.7 | 0.64 | 0.94 | $1.87^{+0.14}_{-0.15}$ | $3.70^{+1.23}_{-1.23}$ | $7.72^{+2.03}_{-1.84}$ | $1.12^{+0.09}_{-0.10}$ | $2.40^{+0.80}_{-0.80}$ | $5.25^{+1.38}_{-1.25}$ | 5 | 1000 |
| A2163 | 0.5 | 0.8 | 0.62 | 0.95 | $2.53^{+0.18}_{-0.18}$ | $3.45^{+1.15}_{-1.15}$ | $19.11^{+4.74}_{-4.06}$ | $1.51^{+0.12}_{-0.12}$ | $2.22^{+0.74}_{-0.74}$ | $12.78^{+3.17}_{-2.72}$ | 90 | 900 |
| A2204 | 0.54 | 0.8 | 0.7 | 0.97 | $2.05^{+0.15}_{-0.16}$ | $3.75^{+1.25}_{-1.25}$ | $9.58^{+2.45}_{-2.22}$ | $1.32^{+0.10}_{-0.10}$ | $2.43^{+0.81}_{-0.81}$ | $6.53^{+1.67}_{-1.51}$ | 5 | 1000 |
| RXCJ2014.8–2430 | 0.69 | 0.8 | 0.71 | 0.98 | $2.03^{+0.25}_{-0.29}$ | $3.80^{+1.27}_{-1.27}$ | $7.86^{+3.80}_{-3.25}$ | $1.16^{+0.16}_{-0.19}$ | $2.47^{+0.82}_{-0.82}$ | $5.37^{+2.60}_{-2.22}$ | 60 | 1000 |
| RXCJ2151.0–0736 | 0.31 | 0.7 | 0.51 | 0.94 | $1.47^{+0.21}_{-0.25}$ | $3.85^{+1.28}_{-1.28}$ | $3.24^{+1.90}_{-1.57}$ | $0.82^{+0.14}_{-0.16}$ | $2.50^{+0.83}_{-0.83}$ | $2.22^{+1.31}_{-1.08}$ | 30 | 1000 |
| A2390 | 0.46 | 0.8 | 0.65 | 0.93 | $2.20^{+0.10}_{-0.10}$ | $3.50^{+1.17}_{-1.17}$ | $14.01^{+2.10}_{-1.91}$ | $1.35^{+0.06}_{-0.06}$ | $2.26^{+0.75}_{-0.75}$ | $9.40^{+1.41}_{-1.28}$ | 50 | 1000 |
| MACSJ2214.9–1359 | 0.27 | 0.3 | 0.39 | 0.83 | $2.03^{+0.19}_{-0.20}$ | $3.10^{+1.03}_{-1.03}$ | $12.90^{+4.42}_{-3.77}$ | $1.17^{+0.12}_{-0.13}$ | $1.98^{+0.66}_{-0.66}$ | $8.39^{+2.88}_{-2.45}$ | 20 | 660 |
| MACSJ2243.3–0935 | 0.2 | 0.5 | 0.42 | 0.86 | $2.18^{+0.17}_{-0.18}$ | $3.15^{+1.05}_{-1.05}$ | $15.74^{+4.34}_{-3.86}$ | $1.29^{+0.11}_{-0.12}$ | $2.01^{+0.67}_{-0.67}$ | $10.29^{+2.84}_{-2.52}$ | 120 | 850 |
| RXCJ2248.7–4431 | 0.49 | 0.7 | 0.57 | 0.9 | $2.19^{+0.14}_{-0.15}$ | $3.30^{+1.10}_{-1.10}$ | $14.89^{+3.26}_{-3.03}$ | $1.32^{+0.09}_{-0.10}$ | $2.12^{+0.71}_{-0.71}$ | $9.84^{+2.16}_{-2.01}$ | 45 | 890 |
| A2537 | 0.37 | 0.6 | 0.52 | 0.87 | $2.25^{+0.12}_{-0.13}$ | $3.35^{+1.12}_{-1.12}$ | $15.77^{+2.82}_{-2.71}$ | $1.37^{+0.08}_{-0.08}$ | $2.15^{+0.72}_{-0.72}$ | $10.46^{+1.87}_{-1.80}$ | 70 | 1000 |
| RXCJ2337.6 + 0016 | 0.19 | 0.7 | 0.55 | 0.88 | $1.99^{+0.11}_{-0.13}$ | $3.50^{+1.17}_{-1.17}$ | $10.56^{+1.96}_{-2.04}$ | $1.21^{+0.07}_{-0.08}$ | $2.26^{+0.75}_{-0.75}$ | $7.08^{+1.32}_{-1.37}$ | 25 | 900 |

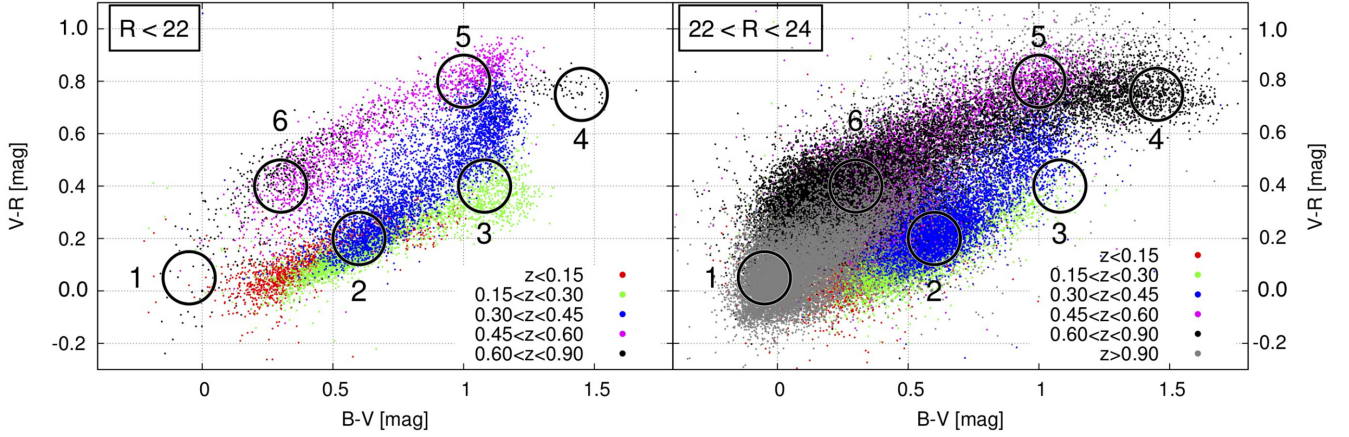


Figure 3. Distribution of COSMOS photo- z galaxies in colour-colour space. *Left-hand panel:* Galaxies brighter than $R = 22$. *Right-hand panel:* Galaxies $22 < R < 24$. Several redshift slices are colour-coded. Circles mark different regions for which redshift distributions are shown in Fig. 4.

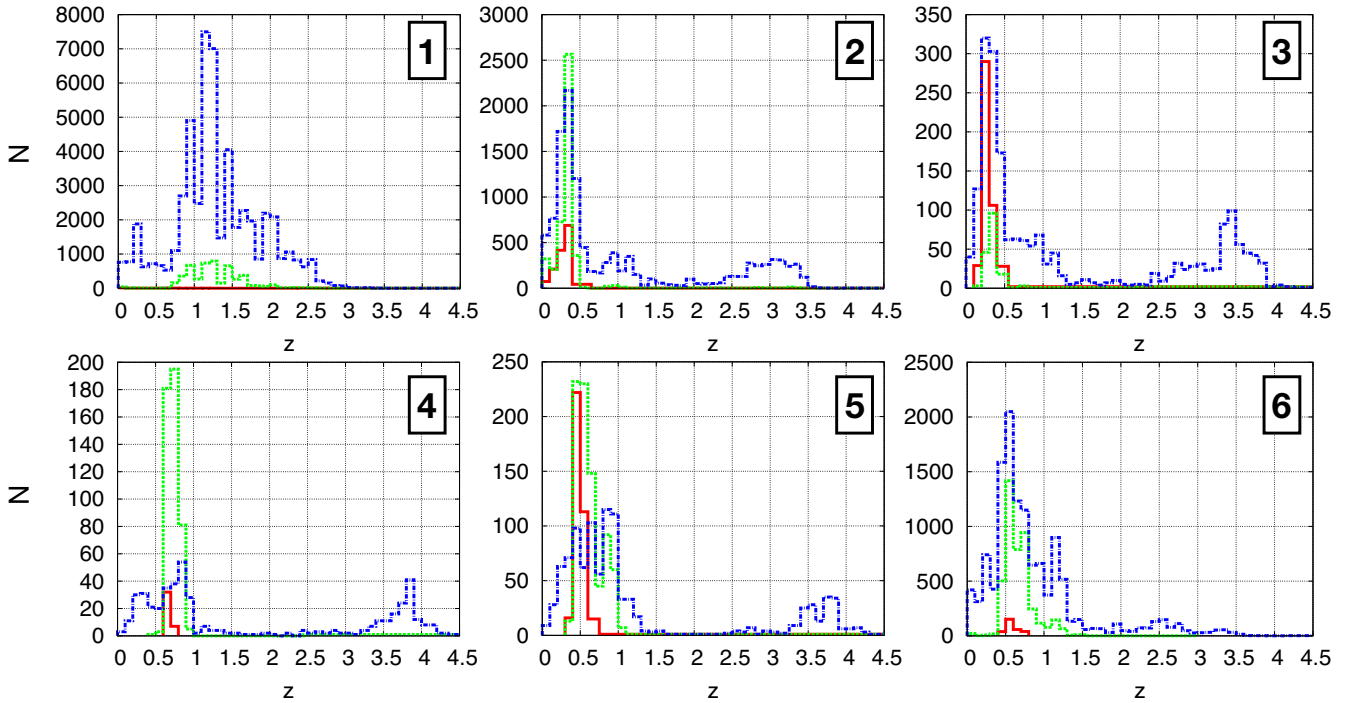


Figure 4. Redshift distribution of galaxies falling in the colour-colour space regions marked in Fig. 3. Red histograms show galaxies brighter than $R = 22$, green histograms galaxies with $22 < R < 24$, and blue histograms galaxies fainter than $R = 24$.

the redshift distributions of the cluster and reference fields. A background selection which avoids manual definition of regions and allows for individual distance estimates is therefore highly desirable, especially in case of large cluster samples.

4.1 CC-diagram of COSMOS

To help the reader to visualize the properties of galaxies in colour-colour-magnitude space, we shortly discuss these on the example of the B , V , R filter set with COSMOS.

As reference photo- z catalogue, we chose the COSMOS photo- z catalogue (Ilbert et al. 2009) because it covers a huge wavelength range with 30 bands, including bands close or identical to our observational data. In terms of depth and image quality, the used

version of the COSMOS catalogue is comparable or deeper than most of our data. The panels of Fig. 3 show the colour-colour diagrams of galaxies in the COSMOS catalogue for magnitudes $R < 22$ mag and $22 < R < 24$ mag. The latter roughly reflects the typical depths of our WFI observations. Different plotting colours indicate different redshift bins.

In these panels, one can recognize regions which are populated with galaxies with a tight redshift distribution, and other regions with a mixture of different redshifts. Investigating the distribution of galaxies of a single-redshift slice, we see that they are arranged in elongated stripes in the cc-diagram. These stripes reflect the diversity of galaxy types, starting at the blue corner (low $B - V$ and $V - R$ values) with strongly star-forming galaxies and ending at the red side with elliptical galaxies with no significant star formation.

The fact that we observe that kind of redshift distribution in the cc-diagram gives us the opportunity to identify red as well as blue cluster members at a certain redshift. In order to highlight how the redshift distribution varies with position in colour–colour and magnitude space, we show in Fig. 4 the redshift distribution of galaxies in six different regions and in three different magnitude bins. For the two brighter magnitude bins, regions with very tight redshift distributions exist, such as Regions 3 and 4. Others, like Regions 1 and 5, show a broader distribution in all magnitude bins. One can also see a magnitude dependency in several regions. Region 1 has basically no sources brighter than $R = 22$ mag but is the densest region in higher magnitude bins. For all except for Region 1, going from the brighter to the fainter subsample, one can see a broadening of the distribution as well as the rise of a second broad peak at $z > 2.5$. The broadening of the distribution comes partially from the increasing photometric errors of the catalogue, but the rise of the high- z peak is also caused by real sources at that redshift. These sources are indistinguishable from lower redshift sources for the filter set we used here. For sources fainter than $R = 24$ mag, the broadening of the redshift distributions results in a mix of a vast redshift range. However, this is not harmful for our purposes: the typical image depth before lensing cuts usually does not exceed $R \sim 24.5$ mag, while size and shear measurement quality cuts further reduce the number of faint sources.

To exclude sources with strong bimodal redshift distributions where one peak is at or below the cluster redshift while the second is at high redshifts, we calculate the probability of a galaxy to be background galaxy p_g for each galaxy g . Requiring a minimum p_g helps to avoid such cases in the lensing catalogue. Additionally, it allows to include galaxies with high probability of being background galaxies, even if the average distance is only slightly above the cluster redshift.

In addition to the limitations due to the available filter set, some limitations arise from the used photo- z catalogue. Before introducing a background selection, these limits of the used photo- z catalogue have to be investigated. One of the major points of concern is the cosmic variance. The volume probed in the two square degree field of COSMOS is smaller for lower redshift ranges, which makes the influence of cosmic variance more prominent. For example, there is no massive galaxy group or cluster below redshift $z < 0.2$ in this field, resulting in the absence of red galaxies of this redshift in the COSMOS catalogue. The lack of these galaxies may influence the background selection but should not effect the mean redshift distribution of the background sample. Cosmic variance at higher redshifts and its effect on the mean lensing depth will be discussed in Section 5.2.

Fig. 5 shows the calibrated cc-diagram of RXCJ 0532 for galaxies brighter than $R = 22$. Overplotted in blue are galaxies from COSMOS with redshifts of $0.27 < z < 0.28$. Comparing with the left-hand panel of Fig. 3, one can see the overdensity of galaxies for redshifts lower than $z = 0.3$, revealing the presence of a massive cluster. The overdensity at Region 3 marks the location of the red cluster galaxies for a cluster at redshift $z = 0.275$.

4.2 Background selection based on COSMOS

To convert the photo- z information in colour–colour–magnitude space (ccm space) into a background selection, we choose the angular diameter distance ratio $\beta \equiv D_{ds}/D_s$ and the purity estimator p , which gives the probability of being a background galaxy,

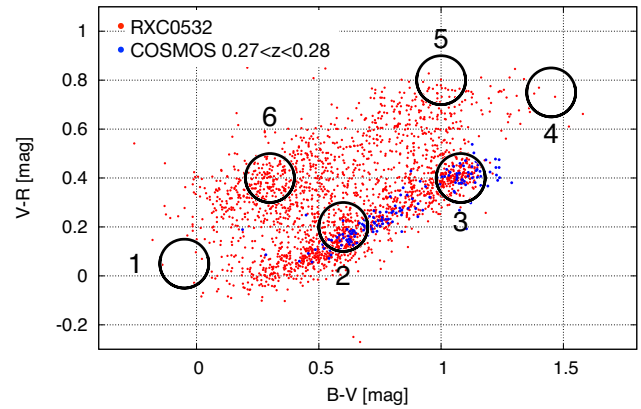


Figure 5. Colour–colour diagram of the RXCJ 0532 cluster field, showing galaxies brighter $R = 22$ mag (red symbols). Blue symbols show galaxies in COSMOS with $0.27 < z < 0.28$ and brighter $R = 22$ mag. The circles mark the same regions as in Fig. 3.

as selection criteria, and calculate these values for each galaxy individually.

Since the shear signal scales with β , the β criterion enables us to exclude regions of ccm space which carry no or only low signal, typical for regions dominated by foreground and cluster galaxies. Because the presence of a massive cluster alters significantly the redshift distribution at low redshifts compared to the distribution in the COSMOS field, the purity estimator can put only a lower limit to the contamination. Since we directly calculate β , we do not need to derive individual redshifts for the galaxies in the lensing catalogue. Nevertheless, the method described below can be used in a similar way to calculate individual redshifts as well.

To calculate β_g for each galaxy g in our lensing catalogue, we apply the following scheme to each source. First, we define an elliptical cylinder in ccm space centred on the position of the galaxy in ccm space. The elliptical base is defined by σ_{c1} and σ_{c2} which are the measurement errors of the two colours measured for this galaxy. Its height is defined by the magnitude uncertainty in the lensing band.

We now use this cylinder to select galaxies in ccm space from the photo- z catalogue. In order to ensure sufficient statistics, we require at least 50 selected galaxies. If not enough galaxies are found, we increase the size of the cylinder by 10 per cent in each direction unless the minimum number of sources or a maximum size (2.5 mag in either colour axis) is reached. In the latter case, we treat the measurement as outlier and set $\beta_g = 0$. Finally, we calculate β_g as the weighted mean of the angular diameter distance ratios (cf. Fig. 2) $\beta(z_d, z_k)$ of the selected galaxies in the photo- z catalogue, with z_k the photo- z of the k th source inside the cylinder, and z_d the cluster (deflector) redshift

$$\beta_g = \frac{\sum_{k=1}^N w(\Delta c_{1,k}, \Delta c_{2,k}) \beta(z_d, z_k)}{\sum_{k=1}^N w(\Delta c_{1,k}, \Delta c_{2,k})}. \quad (10)$$

As weight function $w(\Delta c_{1,k}, \Delta c_{2,k})$, we use a 2D Gaussian function centred on the colours $c_{1,g}$ and $c_{2,g}$ of the lensing catalogue galaxy g , with standard deviations of σ_{c1} and σ_{c2} . The two parameters $\Delta c_{1,k}$ and $\Delta c_{2,k}$ are the differences in colour of the photo- z galaxy k with respect to g ,

$$\Delta c_{1,k} = c_{1,k} - c_{1,g}, \quad \Delta c_{2,k} = c_{2,k} - c_{2,g}. \quad (11)$$

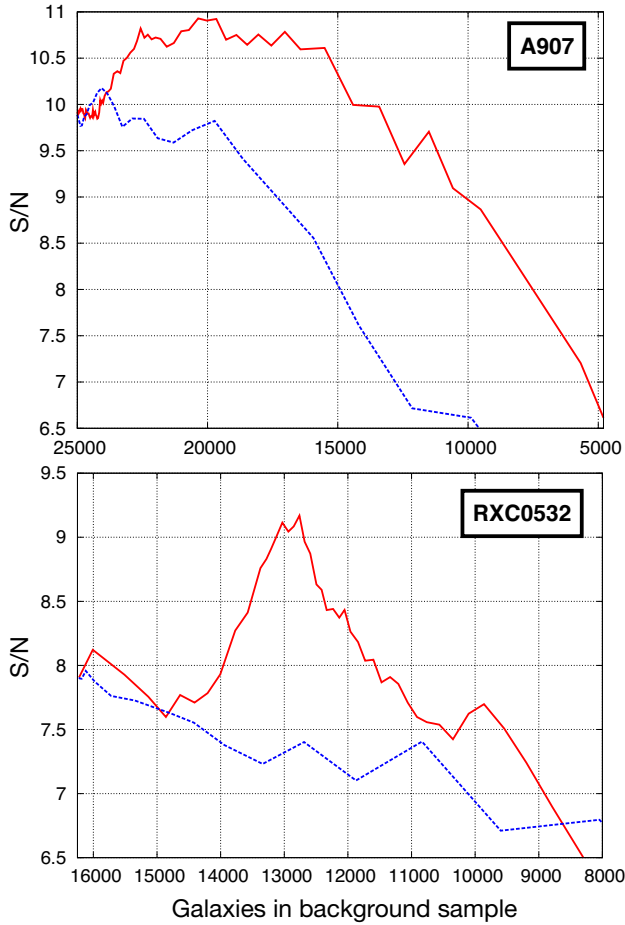


Figure 6. S/N at the cluster position taken from the S -statistics maps versus remaining background galaxies using β_g for selection (red) and magnitude cut (blue) for A907 (top) and RXC0532 (bottom). The abscissa start at the complete catalogue of candidate background galaxies derived in Section 3.3, i.e. $\beta_{\text{cut}} = 0$. Going to the right, β_{cut} increases, resulting in a progressively purer but smaller catalogue.

We restrict our weighting to the colour–colour plane since the magnitude-dependence within the cylinder is much weaker than the colour dependence. A full 3D weighting was tested, but with no significant improvement and higher sensitivity on the zero point calibration. We therefore choose the simpler treatment for our distance estimate.

In the same way as β_g , we can calculate p_g by simply replacing $\beta(z_k)$ with the Heaviside step function $\Theta(z_k - z_d)$:

$$p_g = \frac{\sum_{k=1}^N w(\Delta c_{1,k}, \Delta c_{2,k}) \Theta(z_k - z_d)}{\sum_{k=1}^N w(\Delta c_{1,k}, \Delta c_{2,k})}. \quad (12)$$

A first selection can be made by investigating the dependency of the signal-to-noise of the lensing detection as measured in S -statistics maps (Schirmer et al. 2007) on a minimum cut in β . We can find a β_{cut} which maximizes the S/N at the position of the cluster peak, this we call ‘peak S/N ’. It marks the point from where on the decrease of the number of background galaxies becomes dominant against the effect of a cleaner catalogue on the signal to noise. Fig. 6 shows the peak S/N over the number of galaxies left in the lensing catalogue for A907 ($z = 0.1527$) and RXC0532 ($z = 0.2745$). Instead of using the peak S/N , one can also use the integrated S/N over a certain aperture or S/N threshold as an estimator. For the

majority of the clusters presented in this paper, the so-found β_{cut} is insensitive against which of the estimators is used, but for extreme merger with several shear peaks one can find different values. Those clusters then have to be investigated individually. Despite the fact that the redshift of A907 is lower than the closest cluster in the COSMOS field and therefore red galaxies at that redshift may be lacking, the background selection still yields an S/N increase by 0.8 compared to a magnitude cut or no cut at all. In the case of RXC0532 (Fig. 6, bottom), one can see a clear peak corresponding to a cut at $\beta_{\text{cut}} = 0.27$. For comparison, we also plotted the S/N curve for a simple magnitude cut selection. It excludes galaxies brighter a certain magnitude value. Since both methods depend only on one parameter, we can compare both methods based on the number of galaxies left in the lensing catalogue. Note that the so-found $\beta_{\text{cut, max}}$ is just the lowest reasonable cut that can be made, since lower values yield lower S/N . It provides the reference value for the final estimate of β_{cut} that will be discussed later.

Generally, given the imaging bands we choose, the redshift distribution changes smoothly in the cc-plane. In principle, there is a risk that β could be biased high in highly bimodal redshift distributions, where one peak may lie at or below the cluster redshift. Such galaxies might not be excluded if we use β as the only selection criterion. However, most contaminant foreground galaxies have a higher probability to be located in regions of the cc-plane where the median redshift of the populations is low in the first place. Therefore, a cut in β is sufficient for most of our cluster redshifts and colour combinations. But to avoid stray low- z interlopers in high- z regions of the cc-plane, additionally, we explicitly exclude regions with high contamination (low p) using the purity estimator p and include sources with $p = 1$.

Fig. 7 illustrates the background selection in colour–colour space for two magnitude ranges for the galaxies in the RXC0532 field. Marked in blue are galaxies which are rejected from the lensing catalogue. A detailed discussion about remaining contamination can be found in Section 5.1. The values of β_{cut} , p_{cut} , $\langle \beta \rangle$, and $\langle p \rangle$ can be found in Table 2.

4.3 Accounting for second-order effects

Some systematic effects on the weak lensing mass estimate can be accounted for if the mass or the shear profile is already known. We, therefore, decided for an iterative approach where the previous mass estimate is used to account for the impact of a broad redshift distribution on our estimate of β_g , and to account for difference in redshift distributions of the cluster field and the reference field.

4.3.1 Correction for differences in redshift distributions

As of now, the estimate of β_g assumes that the redshift distribution of the reference catalogue at a given position in ccm space reflects the true redshift probability distribution for that galaxy. Beside variations due to cosmic variance, this assumption becomes increasingly incorrect the more the ccm regions of cluster galaxies and background galaxies start to mix up. As discussed in the previous section, we assume those regions get excluded by our S/N optimization step, as long as the redshift distribution does not get bimodal. Nevertheless, we try to account for this effect in a second iteration of the mass measurement, using the mass from the first measurement.

We estimate the impact of the cluster galaxies on the redshift distribution in a given colour–colour region by splitting the observed

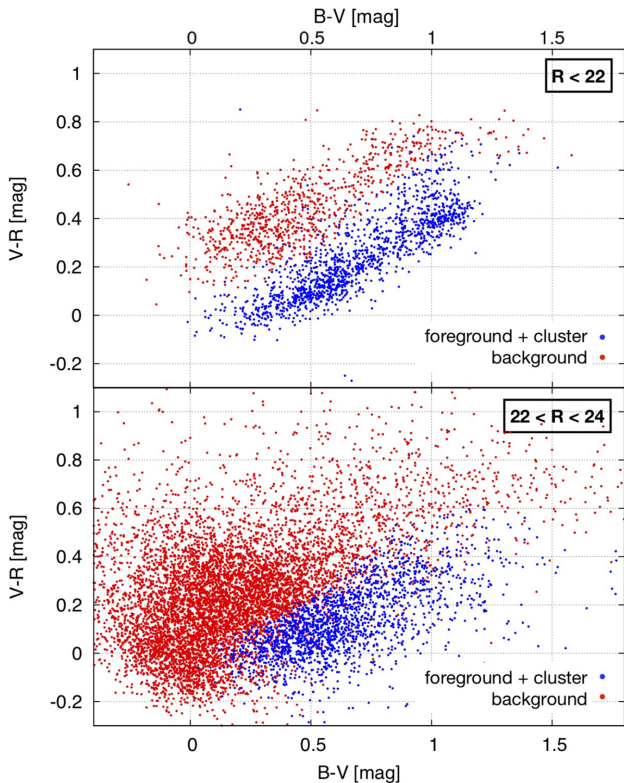


Figure 7. *Top panel:* Galaxies in the RXCJ0532 field brighter than $R = 22$ mag. Blue points mark excluded foreground and cluster galaxies; red points mark background galaxies. *Bottom panel:* The same, but for the magnitude range $22 < R < 24$ mag.

field into several radial bins, depending on our first measurement of r_{200} . For each radial bin, we create a smoothed galaxy density map in colour–colour space. We normalize these maps by dividing them by the map obtained for the outermost bin, which is set to $r > 1.5r_{200}$ or at least outermost 10 per cent of the sources in case of nearby massive clusters. Under the assumption that the outermost bin is close to the cosmic average, the resulting maps show the difference of the redshift distribution within this bin to the cosmic average.

We only aim to account for the strongest effect of the cluster on the redshift distribution, which is caused by the cluster galaxies. More subtle effects such as that caused by the weak lensing magnification effect are ignored.

For any galaxy g in a radial bin b that lies within a colour–colour region with a significant positive peak, we correct the estimated β_g , by dividing the initial β_g by $v_b(c_1, c_2)$, the corresponding value of the normalized maps. This correction assumes each positive peak in those maps to be caused by cluster member galaxies, which do not carry a shear signal. To ensure that we do not select possible clusters at higher redshift than our targeted clusters, we visually investigate the selected regions and compare them with the expected location of cluster members. Performing the correction within several radial bins ensures that radial trends such as the probability of being a cluster member as well as changes in the mixture of galaxy types are captured.

4.3.2 Accounting for broad redshift distributions

The expected reduced shear caused by a cluster can be calculated via equation (5) if β is precisely known. In the absence of a precise

estimate, one has to account for a broad distribution in β . Using β_g derived as a weighted mean over reference sources assumes linear dependence of the reduced shear with β . This is only valid for small κ and γ and becomes increasingly incorrect towards the cluster centre. Although this effect is assumed to be small, we aim to correct for it during the second iteration of the mass estimate. Under the assumption that our first mass estimate of a cluster is approximately correct, we can calculate the expected reduced shear for a given source with cluster-centric distance θ and angular diameter distance β . This allows to recalculate the $\beta_{g,2}$ such that it satisfies the equation

$$g(\theta_g, \beta_{g,2}) = \frac{\sum_{k=1}^N w(\Delta c_{1,k}, \Delta c_{2,k}) g(\theta_g, \beta(z_d, z_k))}{v_b(c_1, c_2) \sum_{k=1}^N w(\Delta c_{1,k}, \Delta c_{2,k})}. \quad (13)$$

In contrast to equation (10), we are now estimating our second step $\beta_{g,2}$ as the value that gives the same reduced shear as the weighted average of the expected reduced shear, calculated from the reference sources at the position of galaxy g . Further, we include the correction term $v_b(c_1, c_2)$ from the previous sub-section to account for redshift distribution differences caused by the cluster itself.

5 INVESTIGATING SOURCES OF SYSTEMATICS AND SCATTER

5.1 Remaining contamination and contamination correction

The background selection by imposing a cut β_{cut} that optimizes the signal does not preclude contamination by cluster and foreground sources. We therefore perform two types of tests to identify remaining contamination by cluster galaxies, first on individual clusters and finally on a stack using all clusters.

5.1.1 Shear profiles from low- z and high- z background galaxy samples

To check for remaining unaccounted contamination, we split the background sample into a low- β and a high- β sub-sample of equal size and investigate the tangential shear of these sub-samples. Since we assume that the low- β (low- z) part will be affected more by contamination than the high- β sub-sample, we expect it to have lower tangential shear, especially towards the cluster centre where the density of cluster galaxies is higher. To account for the different β of the two background samples for a given cluster, we use the assumption that the approximation $g_+ \approx \gamma_+$ holds and therefore the reduced shear scales simply with β . We test this for all clusters in our sample. Fig. 8 shows the binned tangential shear of these sub-samples for the three example clusters. In most cases, both samples agree well with each other, in particular if there is no hint of an increasing dilution towards the cluster centre.

5.1.2 Galaxy density profiles

A frequently used tracer for contamination of the background galaxy sample is the number density of sources in dependency of the radial distance to the cluster centre [e.g. Applegate et al. (2014); Hoekstra et al. (2015); Dietrich et al. (2019)]. The usual assumption is that a clean sample would have a constant number density and contamination by cluster galaxies would show up by an increase of the number density towards the cluster centre. However, several physically and observational effects complicate the interpretation of these plots. The magnification effect can create a similar positive or

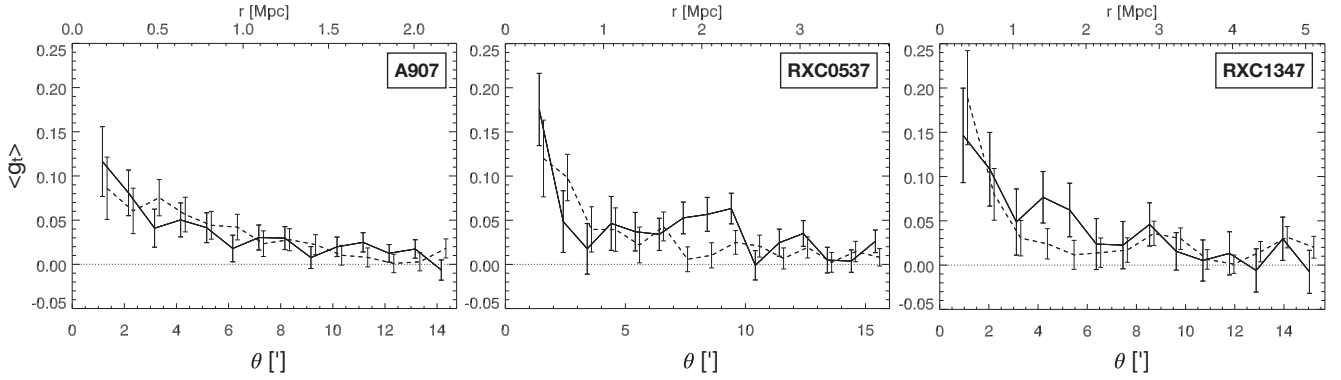


Figure 8. Binned tangential shear for A907 (left), RXC0532 (middle), and RXC1347 (right). The continuous line represents the low-redshift subsample, the dashed line the high-redshift background subsample.

a counteracting negative number density profile, depending on the redshift, brightness, and size distribution of the background galaxy sample. In addition, the obscuration by cluster and foreground galaxies, holes in the data set created by masked areas, changes in the depth of the field, and small-scale clustering can impact the radial density profile, if not accounted for. Finally, one has to account for the next-neighbour filtering in the lensing catalogue which excludes close source pairs from the catalogue to avoid wrong shape and flux measurements. Since the total number density of sources and therefore the probability of close pairs increase towards the cluster centre, this filter has also a radial dependency. This effect is difficult to model, therefore some authors like Applegate et al. (2014, hereafter A14) use a less filtered source catalogue for their contamination estimate rather than the final lensing catalogue. But since close pairs not only effect individual shear measurements but also the photometric quality, the lensing catalogue might be slightly cleaner than the other catalogue used to derive the galaxy density profile, since it avoids sources with blending issues. The number density plots of the lensing catalogues seen in Fig. 9 are accounting for most of the measurement effects except the next-neighbour filtering and small-scale clustering. All plots show a depletion of background galaxy density profiles towards the cluster centre, which can be interpreted as being caused by either the next-neighbour filtering, the magnification effect, or a combination of these effects. The lack of an increase towards the cluster centre at least supports the result of the previous test that there is no obvious cluster contamination left.

5.1.3 Stacked profiles

Individual profiles yield an insight to the cluster-by-cluster performance of the background selection, but do not offer sufficient statistics to search for small amounts of contamination. For this reason, both tests were repeated using a stack of all clusters. We stack the background catalogues, scaling the radial distances by our estimates of r_{200} . For the shear profile test, we split the background galaxy catalogue of each cluster by its median β to ensure that each cluster contributes equally to each sub-sample. To account in a more precise way for the difference in the average β of the sub-samples, we first fit an NFW-based shear profile to the total background sample. We then scale the measured ellipticity of each source by the ratio $g(\beta_g, r)/g(\langle\beta\rangle, r)$, the expected shear for the galaxy at distance r using β_g over the expected shear at the same position using the

average β of the full background sample. The resulting shear profiles are shown in Fig. 10 (left-hand panel). The shear profile fits yield-consistent results for the low- β and high- β stacked background samples, suggesting either a very low unaccounted contamination or that the contamination in both subsets are essentially of the same order.

In case of the stacked galaxy density profile, we normalize the density profile of each cluster by dividing the profile by the median density beyond $1.5 r_{200}$. The right-hand panel of Fig. 10 shows the median of the normalized densities of the individual clusters for each radial bin. Similar to the individual profiles shown in Fig. 9, the stacked density profiles of background galaxies show a clear decrease towards the cluster centre. The density of excluded sources increases by a factor of 2.6 towards the cluster centre.

Despite the encouraging results in Figs 8, 9 and 10, we expect some remaining minimum contamination of up to ~ 14 per cent judging by the mean of the purity estimator as can be seen in Table 2. This contamination of ~ 14 per cent is mainly due to foreground galaxies and should not be related to the presence of a cluster. The remaining contamination is therefore included in our reference catalogue and is of the same amount as for the cluster fields. When calculating β , we therefore automatically include the correct amount of contamination by foreground sources yielding an unbiased estimate of β , and with that of the cluster mass.

5.2 Mean lensing depth and cosmic variance

The reduced shear $g_i(\theta_i)$ exerted by a lens on the image of a background source depends on the ratio of angular diameter distances β , and the resulting cluster masses via equation (9) scale roughly linear with it.

A point of concern in weak lensing is the influence of cosmic variance on the determination of the mean lensing depth. Where unaccounted cosmic variance in a cluster field results in an additional source of noise, the effect of cosmic variance in the reference photo- z catalogue would systematically affect the mass estimate. The cosmic variance on the mean redshift of a COSMOS-sized field can be estimated to be approximately 3 per cent (van Waerbeke et al. 2006). To backup this approximation and to explore how this impacts our measurements, we utilize the COSMOS and the CFHTLS deep fields (Ilbert et al. 2006).

Our background selection estimates β_g for each galaxy. Therefore, it is straightforward to calculate $\langle\beta\rangle$ for the whole cluster field. Cosmic variance can act in two ways on the background sample:

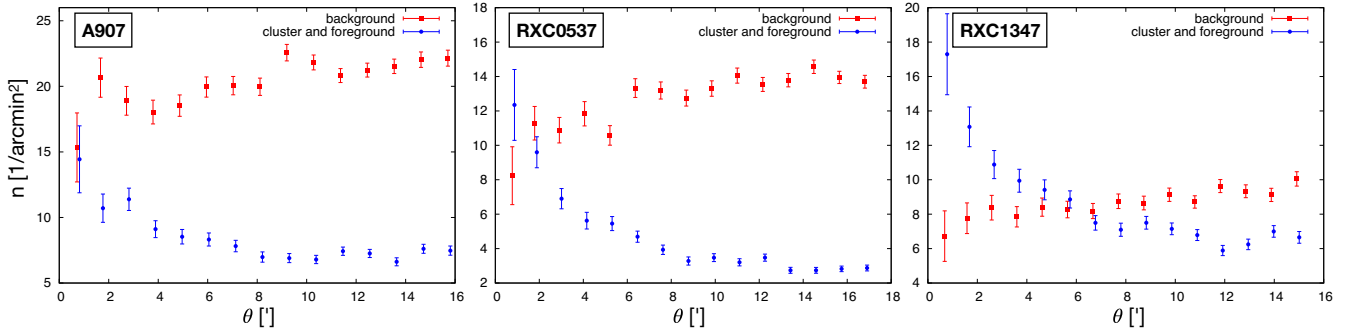


Figure 9. Binned galaxy number density for A907 (left), RXC0532 (middle), and RXC1347 (right). Blue symbols show sources excluded from the lensing catalogue; red symbols show galaxies included in the lensing catalogue.

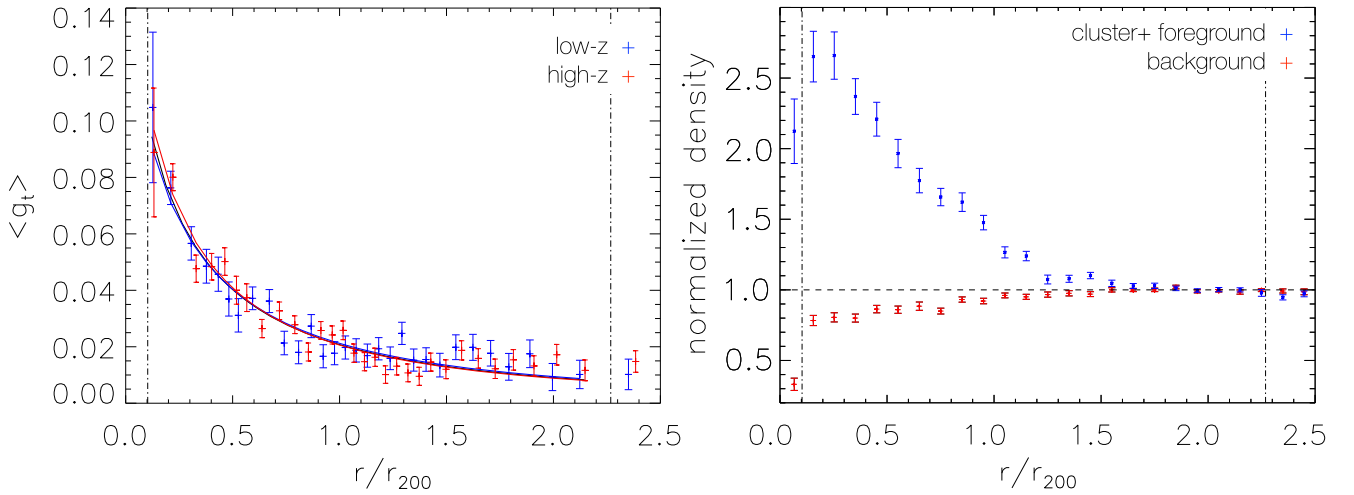


Figure 10. Left: Similar to Fig. 8 but stacking the shear profile of all clusters. The shear of low- z (blue) and high- z (red) background galaxy sample is scaled to the average β of the full sample. The corresponding fits to the different samples are shown as continuous lines with the corresponding colour. The black line shows the fit to the full sample. Right: Similar to Fig. 9 but using stacking all cluster catalogues. Blue symbols show sources excluded from the lensing catalogue; red symbols show galaxies included in the lensing catalogue. The number density of the stacked cluster sample is normalized to one at $2r_{200}$. The vertical dash-dotted line indicated the typical fitting range for the shear measurement.

First, it can change the number density of sources in a certain region in ccm space. Second, it can alter the redshift distribution of a given ccm region with respect to the photo- z catalogue used for our selection. The first effect will not affect the estimate of $\langle\beta\rangle$ or β_i but the second one does.

In order to estimate the level of scatter in $\langle\beta\rangle$ that is induced by the cosmic variance and how far our background selection can reduce the scatter, we explored the behaviour of this quantity in nine individual subfields of the COSMOS field. The size of $30 \text{ arcmin} \times 30 \text{ arcmin}$ of the subfields matches the typical field sizes of our observations. We apply our background selection on these fields by assuming the typical cuts in β for three different cluster redshifts. Afterwards, we measure the mean lensing depth $\langle\beta_{\text{meas}}\rangle_i$ based on our method and the mean lensing depth $\langle\beta_{\text{true}}\rangle_i$ obtained by using directly the COSMOS redshifts of each galaxy for each field i .

The left-hand panel of Fig. 11 shows the mean value of $\langle\beta_{\text{meas}}\rangle_i / \langle\beta_{\text{true}}\rangle_i$ of the nine subfields for different limiting magnitudes and redshifts. The errorbars indicate the standard deviation between the fields. On average, our method recovers the true mean

lensing depth within 0.5 per cent, but significant scatter is found between subfields.

To investigate if this scatter is introduced by cosmic variance or by noise in our method, we measure scatter of the mean true lensing depths between the subfields. The middle panel of Fig. 11 shows the standard deviation between fields over the average of the mean lensing depths over all subfields $s_{\text{cos}} = \sigma_{\langle\beta_{\text{true}}\rangle_i} / \langle\langle\beta_{\text{true}}\rangle_i\rangle$. The scatter introduced through cosmic variance on the mean lensing depth is a string function on imaging depth and cluster redshift, but falls below 4 per cent even for $z = 0.45$ for catalogues reaching depths greater than $R = 24$. At this point, it is important to note that this test assumes approximately similar imaging depths for all subfields in COSMOS and that all fields are uncorrelated. Given the size of the COSMOS field, we expect some correlation between subfields potentially causing an underestimation of the scatter.

To measure by how much our method to derive individual β_g reduces the impact of the variance between fields, we compare the scatter between recovered and measured mean lensing depth $s_{\text{meas}} = \sigma_{\langle\beta_{\text{meas}}\rangle_i} / \langle\langle\beta_{\text{true}}\rangle_i\rangle$ with the scatter found between subfields (s_{cos}). In the right-hand panel of Fig. 11, we show the ratio $s_{\text{meas}}/s_{\text{cos}}$,

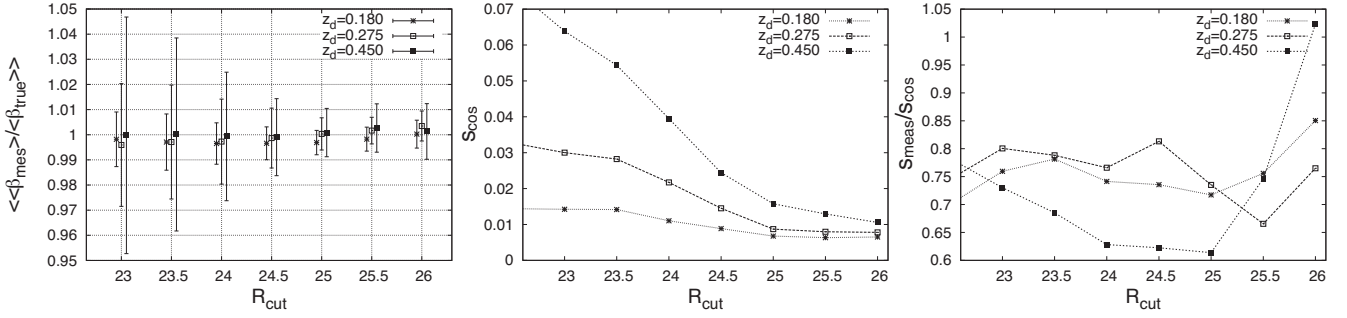


Figure 11. Tests on COSMOS subfields. *Left:* Mean ratio of mean lensing depth measured by our method over true mean lensing depth. The errorbar indicates the field to field scatter (s_{meas}). *Middle:* Scatter in true mean lensing depth between fields divided by the mean over all subfields (s_{cos}). *Right:* Ratio of measured scatter s_{meas} over cosmic-variance-induced scatter s_{cos} . All measurements are for three cluster redshifts and as function of limiting magnitude R_{cut} .

again for different cluster redshifts and limiting depths. We find that the scatter between measured and true mean lensing depth is 20–40 per cent smaller than that caused by cosmic variance between fields.

For individual clusters, the scatter, compared to the typical measurement scatter of ~ 25 , is small enough to be ignored if the imaging depth is high and the cluster redshift low enough. But assuming that the 20–40 per cent reduction in scatter is maintained also for the full COSMOS field, the overall systematic uncertainty on mean lensing depth that comes from the limited size of the COSMOS field is reduced too.

In order to examine the significance of the trends we see in Fig. 11, we mimic repeated observations of the same subfields. To this end, we randomly varied the colours of the individual sources in the photo- z catalogues within their photometric errors. We ignore an additional scatter that may come with an imperfect zero-point calibration.

We created 20 realizations of the same subfield for three of our nine subfields used in our previous test. The scatter of $\langle\beta_{\text{true}}\rangle_i - \langle\beta_{\text{meas}}\rangle_{i,j}$ over all realizations j of a subfield i is of about one order of magnitude smaller than the scatter found for s_{meas} , indicating that the remaining 60–80 per cent scatter seen in the right-hand panel of Fig. 11 is driven by variance of the redshift distributions and not by the scatter in the photometry of the observation.

5.2.1 Cosmic variance on the scales of the reference field

To further investigate the impact of cosmic variance on the mean lensing depth on scales of the size of our reference catalogue, we make use of the four CFHTLS deep fields. They consist of four well-separated one-square-degree fields with five-band (u, g, r, i, z) photometry allowing to derive individual source redshifts (Coupon et al. 2009). We calculate β for all sources, assuming a cluster redshift of $z = 0.3$. We measure the mean β for all fields separately and for the merged catalogue for four r -band limiting magnitudes between $r = 23$ and $r = 24.5$ mag applying a cut in photo- z of $z > 0.5$ to mimic the background selection. The faintest magnitude limit was chosen to ensure that all fields are complete at that magnitude. We find a scatter of 2.5–2.7 per cent among the mean β of the subfields with respect to the mean of the merged catalogue. As the COSMOS catalogue is about twice the size of a single CFHTLS deep field, the expected impact of cosmic variance is therefore lower. Further, as shown in Fig. 11, our method is able to compensate for 25–30 per cent of the scatter introduced by cosmic variance.

Naively imposing a $\sqrt{2}$ scaling in area and a 25 per cent reduction due to our method results in an estimated 1.4 per cent uncertainty caused by cosmic variance within the limited size of the reference catalogue.

5.3 Mean lensing depth and photometric calibration

In this section, we investigate the impact of the limited precision of the photometric calibration on the recovered mean lensing depth, using a sub-set of the COSMOS catalogue as input to our pipeline to estimate angular diameter distance ratios β_g .

5.3.1 Dependency on photometric zero point

To investigate the dependency of $\langle\beta_{\text{meas}}\rangle$ on the estimated ZPs, we use a sub-set of 40 000 randomly selected galaxies from the COSMOS catalogue and vary the overall ZP by ± 0.05 , ± 0.1 and ± 0.2 magnitudes. Those catalogues are then used as input to our pipeline to estimate β_g assuming two different lens redshifts of $z = 0.3$ and $z = 0.45$. The output catalogue is then matched with the catalogue obtained without altering the ZPs. We calculate the difference $\delta\beta_g$ for each source and finally measure the ratio $\langle\delta\beta_g\rangle/\langle\beta\rangle$ for different R band limiting magnitudes. The result of this test is shown in Fig. 12.

We find that the sensitivity of our estimate of the mean lensing depth is mainly a function of imaging depth. The differences between the $z = 0.3$ and $z = 0.45$ cases is very small and reaches a maximum of 0.5 per cent. The difference between estimated mean lensing and true mean lensing depth depends almost linearly on zero-point for offsets of up to ± 0.2 and decreases with increasing image depth. Beside these dependencies, the overall impact of zero-point shifts on the mean lensing depth and stays small for the typical depth of our weak lensing observations. We note that we do not expect a systematic offset in zero-points in our data, since we used a stellar locus based on our reference catalogue.

5.3.2 Dependency on colour offset

From Section 2, we expect a scatter of ~ 0.013 mag in the calibration of the colours. To investigate how the mean lensing depth depends on colour offsets, we repeat the previous test, but varying the colours instead of the overall ZPs. We vary the colours by ± 0.01 , ± 0.02 , and ± 0.03 mag and compare the estimated $\langle\beta_{\text{meas}}\rangle$ to that obtained without shift of relative zero-points. The right-hand panel of Fig. 12

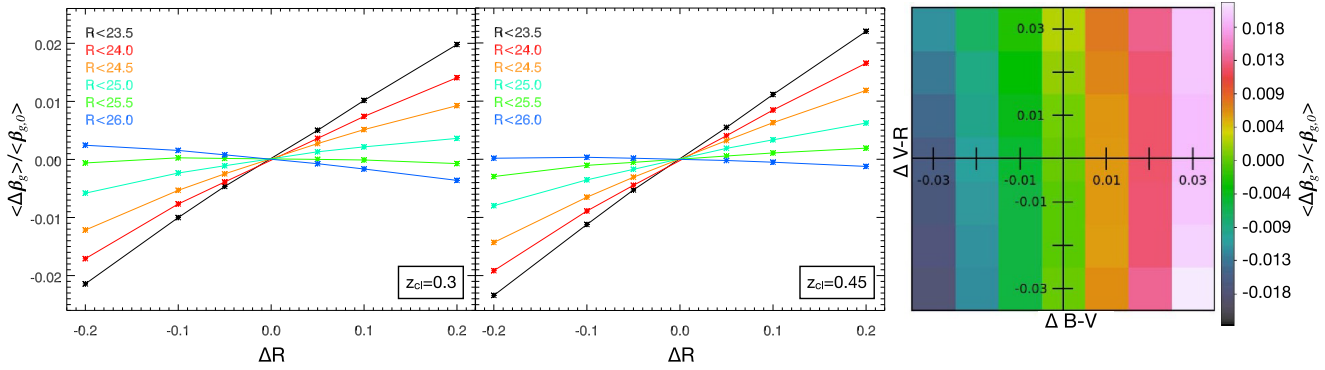


Figure 12. Dependency of estimated β_g on photometric calibration (zero-point calibration and colour calibration). *Left & middle:* Mean difference $\langle \Delta \beta_g \rangle$ between β_g derived with and without altering the R -band magnitude by ΔR over mean β_g of the unaltered galaxy sample, for different depths and cluster redshifts. *Right:* Dependency on shifts in colour for a $z = 0.3$ cluster.

shows the outcome of this test, assuming a cluster at $z = 0.3$. The colour-coded cells display $\langle \beta_{g,\Delta} - \beta_{g,0} \rangle / \langle \beta_{g,0} \rangle$, the ratio of the mean difference between β_g evaluated with colour shift and without colour shift, over the average β_g without colour shift. The impact of relative zero-point shifts is stronger for $B - V$ shifts compared to $V - R$ shifts. For colour shifts of ~ 0.013 mag, the average lensing depth changes by 1.3 per cent.

By construction, we do not expect the overall or the relative zero-points to be systematically off from the reference catalogue. Therefore, colour and zero-point shifts only contribute to the overall mass-to-weak lensing mass scatter. Presuming no correlation between the scatter in zero-points and colours, the overall scatter in β can be estimated to be $\sigma \approx \sqrt{1.3^2 + 0.6^2} = 1.4$ per cent, where 0.6 per cent comes from the 0.05 mag scatter of the absolute zero-point for $R = 24$ depth. This is small compared to the expected scatter between true mass and weak-lensing-based mass and is of the same order as the scatter introduced by cosmic variance.

5.4 Shear calibration bias

The used KSB + shape measurement pipeline is known to recover biased measurements for sources with low signal-to-noise ratio (Erben et al. 2001; Heymans et al. 2006). Israel et al. (2010, 2012) used a signal-to-noise threshold of 4.5 above which a constant shear calibration factor of 1.08 (or 8 per cent) is assumed. The high number of clusters in this sample allows us to investigate the signal-to-noise dependent shear calibration bias in greater detail. For each cluster, we measure the radius r_{200} for different signal-to-noise thresholds and normalize them by dividing each r_{200} by the median over all thresholds. For each threshold, we derive the median over all clusters, the standard deviation, and the error on the mean, by dividing the standard deviation by the number of clusters.

Fig. 13 shows how the normalized scale radius r_{200} depends on a signal-to-noise threshold. The black error bars show the standard deviation of the distribution of values around the mean, while red error bars show the error on the mean. The mean scale radius stays constant beyond a threshold of 5.25–5.5. Using galaxies with lower signal-to-noise values can underestimate the scale radius by up to 5 per cent. For our analysis, we therefore choose a threshold of 5.5 for our conservative model and 4.5 for a signal-to-noise optimized model. Following Israel et al. (2010, 2012), we assume a systematic uncertainty on the shear calibration bias of 0.05, corresponding to 4.6 per cent.

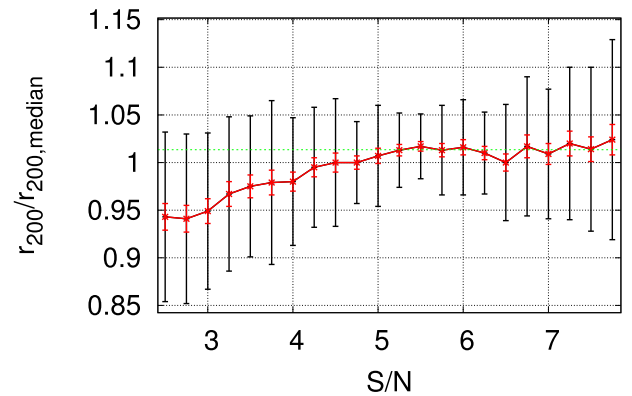


Figure 13. Mean virial radius as a function of the signal-to-noise threshold. Black error bars indicate the standard deviation of the estimated virial radii while red error bars show the error on the mean value. The mean value above signal-to-noise greater than five is shown as green dotted line.

To convert this uncertainty to cluster mass, we investigate the response of the mass estimate on variations on the assumed shear calibration bias. For that, we created synthetic, NFW-based, shear profiles spanning the full redshift and mass range of our sample using the Bhattacharya et al. (2013) $c-M$ relation. We find that the response of the cluster mass on the uncertainty of the multiplicative shear calibration factor to be described by a linear relation with slope 1.4. We further find a small approximately linear dependency of the response on cluster mass and redshift, where we find 1.35 to be the lowest slope (reached at low mass and low redshift) and 1.45 as the highest slope (high mass and high redshift). Given the redshift and mass distribution of the cluster sample, the value of 1.4 is a sufficiently good approximation for the vast majority of the sample. An uncertainty of 4.6 per cent in shear calibration therefore translates into 6.5 per cent in cluster mass. We note that the same response also holds, to first order, for uncertainties in mean lensing depth $\langle \beta \rangle$. The uncertainty of 1.4 per cent associated to cosmic variance in the cosmos field, corresponds to ~ 2 per cent uncertainty in mass.

5.5 Selection induced bias

The background selection relies on the optimization of the shear signal of the cluster. Since the shear signal is a noisy property, there is some chance to use a peak boosted by noise to select the value

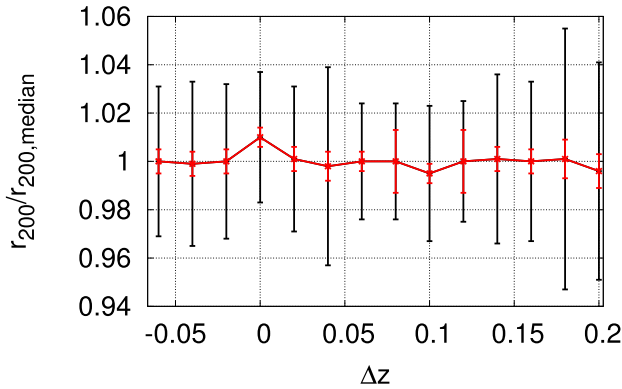


Figure 14. Mean virial radius as a function of β_{cut} , parametrized in $\Delta z = z_{\text{cut}} - z_{\text{cut, max}}$. Black error bars indicate the standard deviation of the estimated virial radii while red error bars show the error on the mean value.

for β_{cut} . This results, on average, in mass estimates biased high compared to the true lensing mass. We use the same method as described in the previous sub-section to investigate the selection-induced bias. We vary β_{cut} , parametrized by the offset Δz from the redshift $z_{\text{cut, max}}$ (corresponding to $\beta_{\text{cut, max}}$) which maximizes the lensing signal-to-noise (cf. Fig. 6). As visible in Fig. 14, the scale radius is biased high at offset $\Delta z = 0$, meaning exactly at $\beta_{\text{cut, max}}$. To both sides of this value, the scale radius stays constant. The fact that even a β_{cut} slightly below $\beta_{\text{cut, max}}$ gives similar masses than $\beta_{\text{cut}} > \beta_{\text{cut, max}}$ indicates that the background catalogue is already free of unaccounted cluster members and that the increase in the signal-to-noise ratio of the lensing detection arises mainly by cleaning the catalogue from foreground sources. The constant value of the scale radius at higher β_{cut} also supports the good quality of our lensing analysis, since average redshift as well as average signal-to-noise of galaxies in the background sample changes significantly with increasing β_{cut} . We choose $\delta z = 0.04$ for our conservative model, to avoid the bias caused by the selection of $\beta_{\text{cut, max}}$. For the signal-to-noise optimized model, we choose $\delta z = 0.0$, this counteracts the underestimation caused by the chosen signal-to-noise threshold. While the conservative model is intended to be used for future scaling relation studies, the signal-to-noise optimized selection is used for the construction of κ -maps.

5.6 Profile fit based systematics

Simulations have shown that weak lensing masses, derived by fitting a single radial NFW-based shear profiles, show significant intrinsic scatter of ≈ 20 percent and a mass-dependent bias due halo triaxiality, correlated and uncorrelated large-scale structure (Becker & Kravtsov 2011; Bahé, McCarthy & King 2012; Lee et al. 2018). Given the number of clusters in this sample, this scatter places a systematic limit of 20 per cent/ $\sqrt{39} \sim 3.5$ per cent on the accuracy of the mass scale for the overall sample. The NFW profile is a good approximation of the dark matter density profile within the virial radius, but gets increasingly discrepant from the truth while going beyond the virial radius. Therefore, A14 restricts the fitting range to 0.75–3 Mpc. However, the same study showed that extending the fitting range out to 5 Mpc results in a insignificant decrease of the mass by $1.3^{+1.2}_{-1.0}$ per cent. Our fitting range extends on average between 0.2 and 4.1 Mpc, which is larger than that used in A14 but also fitting closer to the cluster core. Re-measuring masses within 0.75–3 Mpc, we find a median mass ratio $M_{\text{Default}}/M_{0.75-3.0} = 0.989 \pm 0.033$ or -1.1 ± 3.3 per cent. Given the small difference

between both fitting ranges investigated in A14, we do not expect that the fitting ranges chosen by us yield different results with respect to A14. We therefore assign the same systematic uncertainty of 3 per cent in mass to the shear profile fitting.

5.7 Summary on sources of systematics and scatter on the weak lensing analysis

Taking the work of A14 as a template, we summarize the different contributions to the overall systematic uncertainty, the total uncertainty is then assumed to be the square-root of the sum of squared uncertainties. The uncertainty on shear calibration of 0.046 (Israel et al. 2010) contributes a mass uncertainty of 6.5 per cent. The scatter between true mass and WL-inferred mass is assumed to be ~ 20 per cent (Becker & Kravtsov 2011; Bahé et al. 2012) for a single cluster. Given our sample size, this results in a 3.5 per cent uncertainty on the sample-wide mass scale. The choice of fitting a NFW profile within 4.1 Mpc results in an uncertainty of 3 per cent. Finally, from the scatter between different CFHTLS fields, we expect the uncertainty of our reference catalogue due to cosmic variance to be 1.4 per cent in β , corresponding to 2 per cent scatter in mass. This results in an overall systematic uncertainty of 8 per cent, where the main contribution comes from the shear calibration.

6 RESULTS

The main focus of this paper is to provide the mass measurements for the APEX-SZ cluster sample. We therefore first describe and discuss the results for the entire sample in Section 6.1. Later, in Section 6.2, we discuss in detail the obtained results for the three example clusters from the sample. We stress that the measurement errors given throughout this work include only statistical errors from the fit to the shear profiles.

6.1 Results using the full cluster sample

In this sub-section, we concentrate on few properties related to the full or a large sub-set of the cluster sample. The inferred weak lensing masses can be found in Table 2.

6.1.1 Comparison to previous publications

Our cluster sample has a significant overlap with three other weak lensing cluster studies, the Canadian Cluster Comparison Project [CCCP, Hoekstra et al. (2015)], Weighing the Giants [WtG, Applegate et al. (2014)] and the Local Cluster Substructure Survey [LoCuSS, Okabe & Smith (2016)] cluster samples. While the WtG and LoCuSS samples partially use the same raw data as our work, the CCCP sample is based on imaging data from a different telescope and instrument. All publications assume the same reference cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $h \equiv H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) = 0.7$. This allows us to directly compare the mass estimates at identical overdensities Δ . Hoekstra et al. (2015) provide masses at $\Delta = 500$, Okabe & Smith (2016) additionally offer the estimates $\Delta = 200$ to compare with our measurement.

For the 10 clusters we have in common with the LoCuSS sample, we find a median ratio ($M_{\text{LoCuSS}}/M_{\text{APEX-SZ}}$) of 0.99 for $\Delta = 200$ and 1.08 for $\Delta = 500$. We see that one cluster, A907 strikes out from the distribution with a mass ratio 4.2 at $\Delta = 200$. Omitting this cluster, we obtain an average mass ratio of 0.96 (1.05) for $\Delta = 200$ ($\Delta = 500$) and a standard deviation of 0.3 for both overdensities. Under

the assumption that the error on the mean is $0.3/\sqrt{9}$ and considering the additional 8 per cent systematic uncertainty, our mass estimates are in agreement with those given by Okabe & Smith (2016).

In case of the CCCP cluster sample, we find 11 clusters that are in common with the APEX-SZ sample. Hoekstra et al. (2015) provide two different mass estimates, one is based on aperture mass, the other one is based on fitting an NFW profile to the shear. We find a median mass ratio ($M_{\text{CCCP}}/M_{\text{APEX-SZ}}$) of 0.86 and 0.84 for the aperture-based and NFW-based masses, respectively. Furthermore, we find an average ratio of 0.95 and 1.09, respectively. The standard deviation is found to be 0.3 for the aperture-mass-technique-based masses and 0.45 for the NFW profile fit. Using the same assumptions as in the previous paragraph, we find 0.09 and 0.14 as error on the mean for the aperture and the NFW-based mass ratios. We therefore do not find any significant bias between our work and that of Hoekstra et al. (2015).

We find 10 clusters in common with WtG cluster sample. The masses given in WtG are given within a fixed radius of 1.5 Mpc and were obtained using a fixed concentration of 4.0 at r_{200} . We approximate the mass within 1.5 Mpc using our NFW fit results at r_{500} . The median mass ratio for WtG is 1.12 and the average is 1.25. The scatter of the mass ratio is 0.34, which yield under aforementioned assumptions an uncertainty of 0.13. The median mass ratio to WtG is therefore within one standard deviation, the mean mass ratio two standard deviations higher than our estimates. We note that we find concentrations <4 at r_{200} for all clusters that overlap with WtG, which might contribute to the mass offset seen here.

To summarize, we see reasonable agreement between our mass estimates and those from literature, with the largest offset seen in the comparison with WtG.

6.1.2 Concentration parameter

In contrast with some weak lensing studies with large numbers of clusters (Hoekstra et al. 2012; Applegate et al. 2014), we provide weak lensing measurements with and without leaving the concentration free to vary. Since weak lensing generally offers only weak constraints on the concentration, we use the full sample of 39 clusters to study the recovery of the average concentration. This test does not aim to perform a detailed study of the mass–concentration relation but it allows to test for consistency between measured and predicted concentrations. Inconsistency between predicted and observed concentration would impact our lensing masses. This analysis is additionally motivated by the low concentrations found in the study of eight galaxy clusters by Israel et al. (2012). Our analysis shares a significant amount of code and methods with Israel et al. (2012). Furthermore, the measurement of low concentrations could be caused by remaining cluster contamination diluting the shear signal towards the cluster centre. The absence of such an underestimation therefore would further support the quality of our analysis even if the measurement accuracy of the concentration for individual clusters is poor.

As in Israel et al. (2012), we compare our results with that of the $c - M$ scaling relation by Bhattacharya et al. (2013), as one of only few simulations covering a sufficiently large volume to probe the high-mass range covered by our sample. The results in Bhattacharya et al. (2013) are based on three simulations with different box sizes and mass resolutions. The Λ CDM parameters used in that simulations are close to the results of WMAP-7 (Komatsu et al. 2011) and the large box size allows better constraints for the high-

mass part of the scaling relation compared to previous studies. This is of special importance for our study since our clusters occupy the highest mass range studied in most simulations. Bhattacharya et al. (2013) found that the concentration parameter can be expressed as a function of the peak height parameter ν as follows:²

$$c_{200, \text{BHH12}}(\nu) = 5.9\nu^{-0.41} D(z)^{0.54}, \quad (14)$$

for all systems and

$$c_{200, \text{BHH12}}(\nu) = 6.6\nu^{-0.35} D(z)^{0.53}, \quad (15)$$

for relaxed systems. Here $D(z)$ is the linear growth factor for a flat Λ CDM universe. The distribution of the concentrations in the simulations can be described by a Gaussian with variance of $\sigma_c = 0.33c$. Using the connection between ν and the cluster mass as described in the above-mentioned paper, we can derive the expected concentration parameters for each of the clusters.

The ratio between our c_{200} measurements before applying a prior on concentration over the concentrations obtained with the mass–concentration relation versus M_{200} is shown in the top panel of Fig. 15. The bottom panel of Fig. 15 shows the histogram of the ratios between observed and predicted concentration in log space. The distribution is well described by a Gaussian function with a mean of -0.02 ± 0.05 . This corresponds to 0.95 in linear space and uncertainty of 12 per cent. We again stress that Fig. 15 is of indicative purpose only. A proper study of the mass–concentration relation would require significantly more effort such as the inclusion of the scatter in the applied $c - M$ relation, proper modeling of the errors in concentration, the correlation with mass, and the modeling of the selection function.

The mean ratio is consistent with one, further it is close to the underestimation of 7 per cent predicted by Bahé et al. (2012) for weak lensing studies. Given this results we do not expect that our weak lensing results are significantly affected by our choice of using a $c - M$ scaling for our default mass estimates.

6.2 Discussion of the example clusters

A detailed discussion of each cluster is beyond the scope of this paper and a small number of selected clusters will be further discussed in light of multifrequency studies. We therefore only discuss here the three clusters used as examples in this publication to some greater detail.

6.2.1 A907

The excellent Suprime–Cam data for this cluster and its low cluster redshift result in a high number density of background galaxies of $n = 20.5 \text{ arcmin}^{-2}$. Our results as listed in Table 2 and illustrated in Fig. 16 are consistent with X-ray measurements by Zhang et al. (2008) and Nulsen, Powell & Vikhlinin (2010) which derive masses between $M_{500} = 3.2 \times 10^{14}$ and $M_{500} = 4.7 \times 10^{14} M_{\odot}$. Ettori et al. (2010) estimated R_{200} using X-rays to be $R_{200} = 2.18 \pm 0.17$ Mpc. This measurement disagrees with our estimate of $R_{200} = 1.61^{+0.12}_{-0.11}$ Mpc. The iso-density contours of the κ reconstruction as seen in Fig. 16 are elliptical and show a slight elongation to the south-east. The semimajor axis of the contours and that of the BCG are aligned into the same direction.

²We use the fitting formula for $\nu(M, z)$ from table 2 of Bhattacharya et al. (2013).

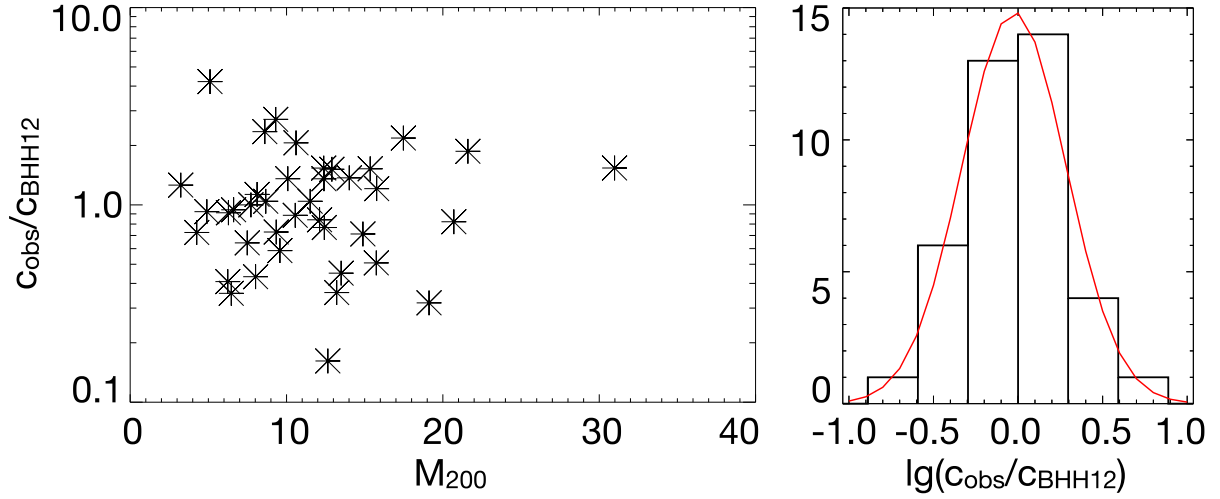


Figure 15. Left-hand panel: Ratio of observed over predicted concentration versus measured M_{200} . Right-hand panel: Histogram of ratios of observed over predicted concentration in log space. The red line shows the fitted Gaussian function. The fit yields a mean of -0.02 ± 0.05 , which corresponds to 0.95 in linear space.

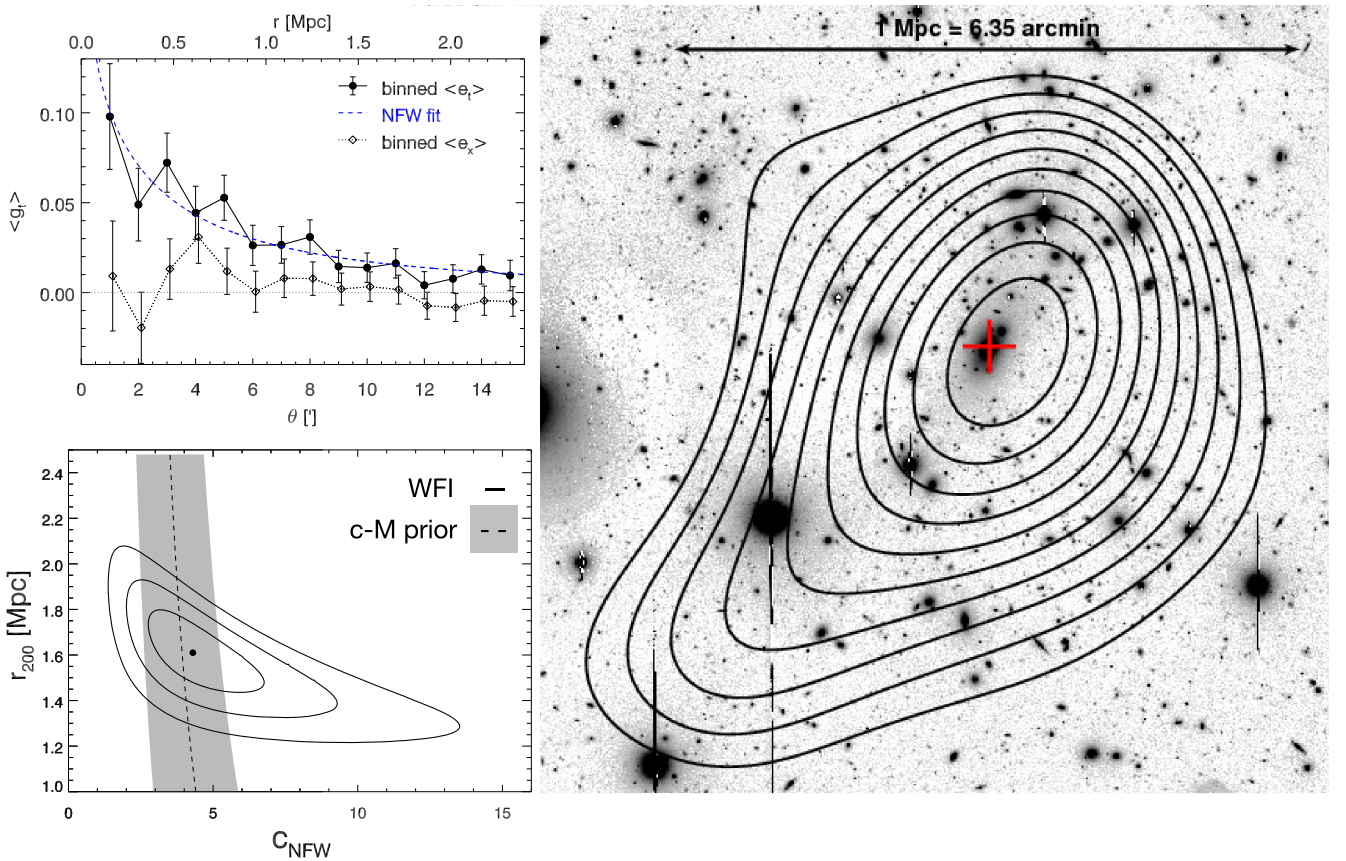


Figure 16. Lensing results for A907. Top left-hand panel: Profiles of the binned tangential ($\langle \epsilon_t \rangle$, filled circles) and binned cross ($\langle \epsilon_x \rangle$, open diamonds) ellipticities. Error bars reflect the bin dispersion. Lower left-hand panel: $\Delta \chi^2(r_{200}, c_{\text{NFW}})$ with respect to its minimum, (filled circle); contours indicating 1σ, 2σ, 3σ confidence levels without c-M prior. Dashed line and gray shaded area shows the adopted c-M relation and one σ uncertainty region. Right-hand panel: R-band image of the central region overlaid with κ contours using $\kappa = 0.05$ in steps of $\Delta \kappa = 0.01$. The black contours show the detection optimizing background selection case (Table 2). The red cross marks the BCG which we defined as the cluster centre.

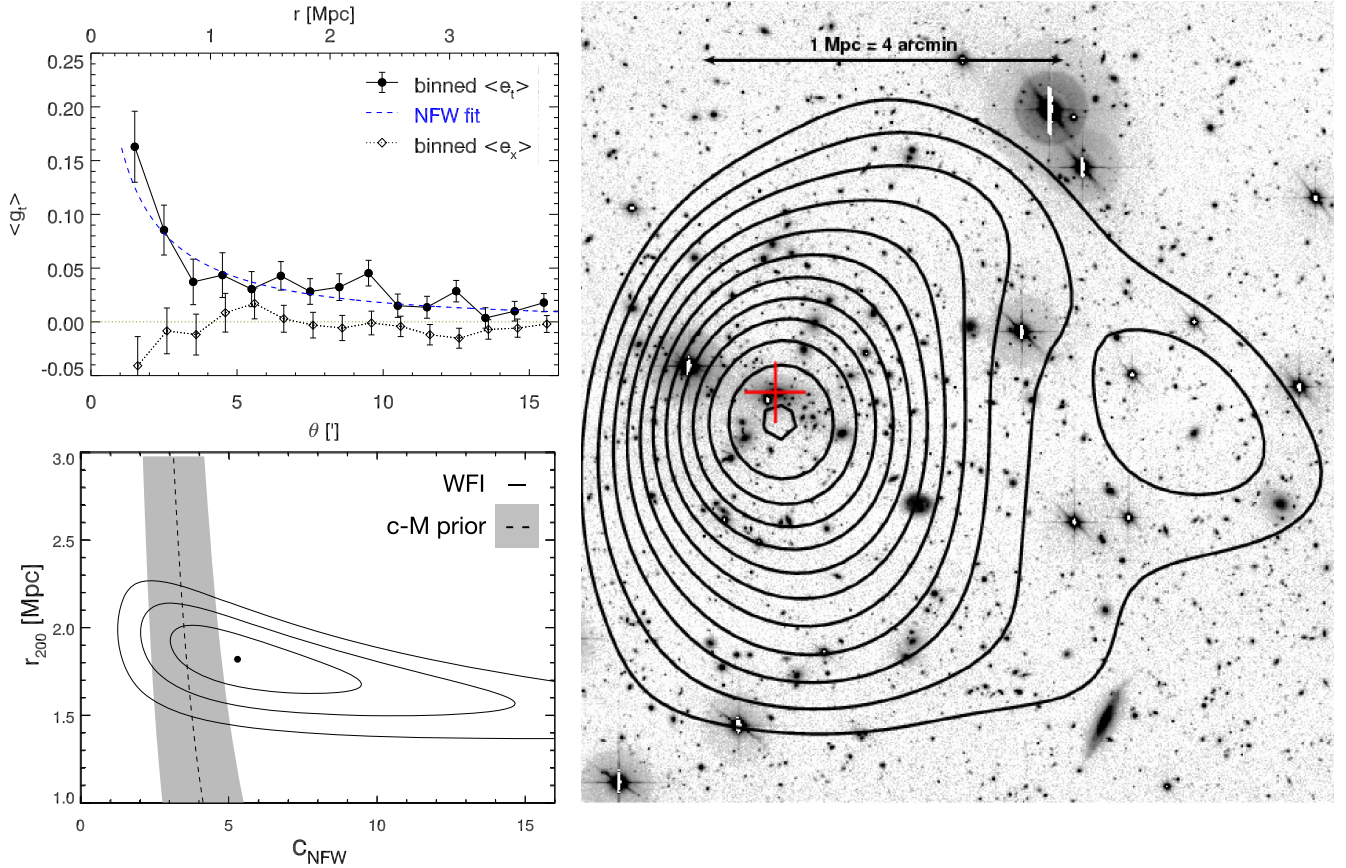


Figure 17. Lensing results for RXC0532. *Top left-hand panel:* Profiles of the binned tangential ($\langle \epsilon_t \rangle$, filled circles) and binned cross ($\langle \epsilon_x \rangle$, open diamonds) ellipticities. Error bars reflect the bin dispersion. *Lower left-hand panel:* $\Delta\chi^2(r_{200}, c_{\text{NFW}})$ with respect to its minimum (filled circle), contours indicating 1σ , 2σ , 3σ confidence levels without c-M prior. Dashed line and gray shaded area shows the adopted c-M relation and one σ uncertainty region. *Right-hand panel:* R-band image of the central region overlaid with κ contours using $\kappa = 0.05$ in steps of $\Delta\kappa = 0.01$. The black contours show the detection optimizing background selection case Table 2. The red cross marks the BCG which we defined as the cluster centre.

6.2.2 RXC0532

The results of RXC 0532 as listed in Table 2 and shown in Fig. 17 show the smallest relative errors on mass out of the three example clusters presented in this paper. Our estimated R_{200} of $1.82^{+0.12}_{-0.12}$ Mpc fits well with the two results of Ettori et al. (2010) of 1.78 ± 0.18 and 1.84 ± 0.23 Mpc based on X-ray observations. Using our best-fit NFW parameters we get a mass of $M_{500} = 7.4^{+1.6}_{-1.4} \times 10^{14} M_{\odot}$. This is slightly discrepant with the estimate by the Planck Collaboration (Planck Collaboration et al. 2011) which, using a $M_{500} - Y_{X,500}$ scaling relation, derive a mass of $M_{500} = 5.35 \pm 0.17 \times 10^{14} M_{\odot}$.

6.2.3 RXC1347

RXCJ1347, as the most X-ray luminous galaxy cluster known, was the object of several detailed studies. Our results shown in Table 2 and Fig. 18 show excellent agreement with the result of Umetsu et al. (2011) which obtain of $M_{200} = 14.3 \pm 3.5 \times 10^{14} M_{\odot}$ for a non-parametric de-projection analysis and $M_{200} = 19.1^{+3.6}_{-3.3} \times 10^{14} M_{\odot}$ for a NFW fit on the deeper Suprime-Cam data. Also, the weak lensing mass from Lu et al. (2010) of $M_{\text{vir}} = 18.9^{+5.9}_{-5.5} \times 10^{14} M_{\odot}$ using the Megaprime instrument on CFHT agrees well with our measurement of $M_{\text{vir}} = 18.3^{+4.9}_{-4.0} \times 10^{14} M_{\odot}$ extrapolated the virial radius.

Our result also agrees with the X-ray mass estimates of Gitti, Piffaretti & Schindler (2007) which derive $M_{200} = 11.0 \pm 2.8 \times 10^{14} M_{\odot}$ for the best Cavaliere & Fusco-Femiano (1978) β profile and $M_{200} = 17.9 \pm 2.1 \times 10^{14} M_{\odot}$ for the best NFW profile fit. The WFI data are shallower than the Subaru ones but show excellent agreement with them. We highlight that these results have been obtained with independent instruments and different filter sets. It is remarkable that we have a similar or higher number density of background sources for the lensing analysis as Umetsu et al. (2011) despite using shallower data. This can partially be explained by the different data reduction pipelines yielding different seeing in the co-added image, but the lower mean lensing depth of $\langle \beta \rangle = 0.35$ compared to $\langle \beta \rangle = 0.49$ indicates that we use a background sample with lower mean redshift in our sample than Umetsu et al. (2011).

7 CONCLUSION AND FUTURE PERSPECTIVES

In this paper, we presented the weak lensing analysis of 39 galaxy clusters, observed as part of the APEX-SZ cluster sample. We presented and discussed a background selection method which calculates the angular diameter ratio β for each galaxy based on observations in three broad-band filters. We investigated the remaining contamination by cluster galaxies using the binned

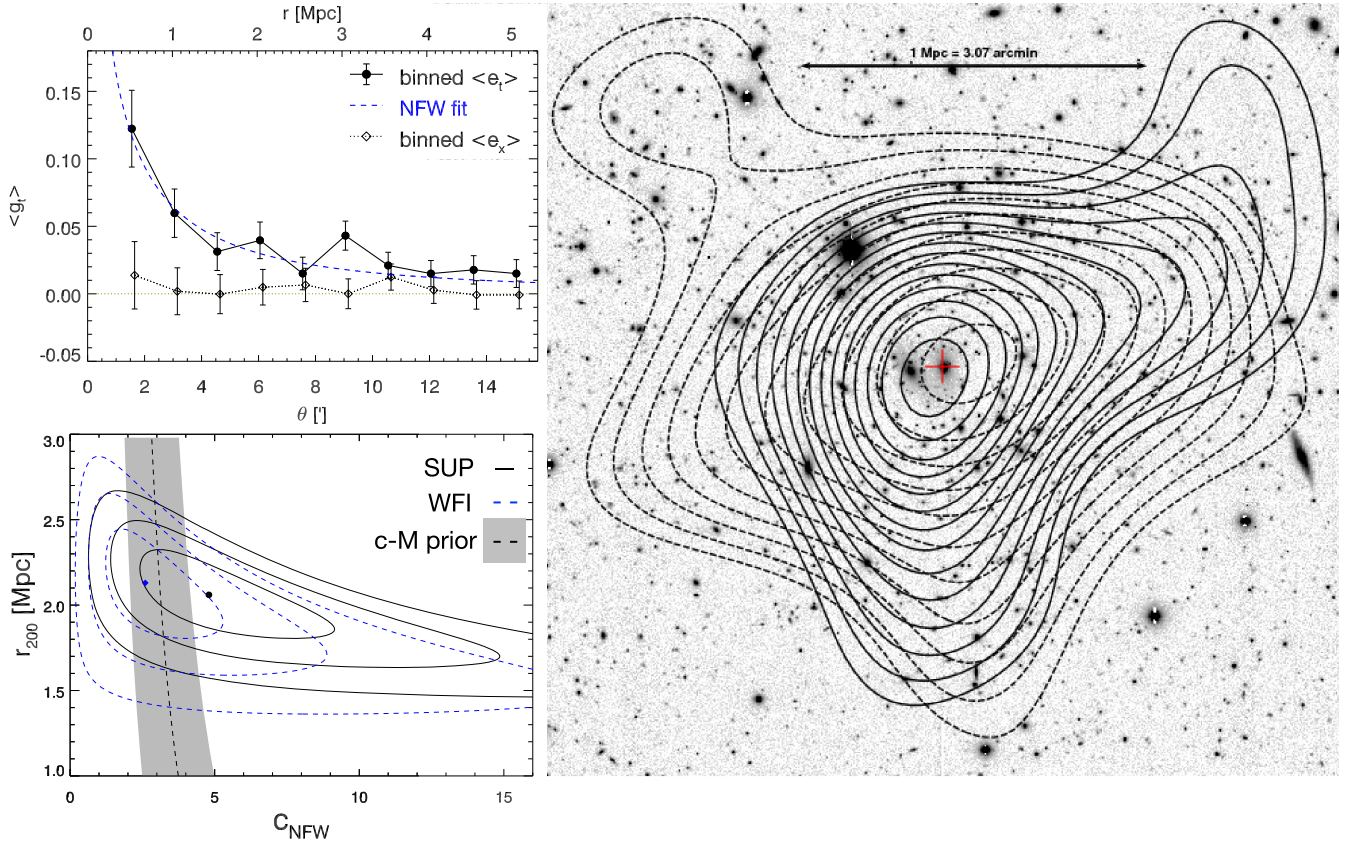


Figure 18. Lensing results for RXC1347. *Top left-hand panel:* Profile of the binned tangential ($\langle \epsilon_t \rangle$, filled circles) and binned cross ($\langle \epsilon_x \rangle$, open diamonds) ellipticities. Error bars reflect the bin dispersion. Based on the SuprimeCam data. *Lower left-hand panel:* $\Delta \chi^2(r_{200}, c_{\text{NFW}})$ with respect to its minimum. Black lines correspond to SuprimeCam measurements, blue dashed lines to WFI based measurements. Dashed line and gray shaded area shows the adopted c-M relation and one σ uncertainty region. *Right-hand panel:* R-band image of the central region overlaid with κ contours using $\kappa = 0.05$ in steps of $\Delta \kappa = 0.01$. Solid lines represent the results obtained with SuprimeCam the dashed lines the results obtained with WFI. The red cross marks the BCG which we defined as the cluster centre.

shear profiles of two different sub-samples of background galaxies, a method insensitive to holes in the data set. Additionally, we investigated the radial number density profiles of the background galaxy sample. Both methods did not show significant hints of contamination by cluster members. Based on the COSMOS photo- z catalogue we showed that cosmic variance can result in a scatter of the mean lensing depth $\langle \beta \rangle$ of 1–3 percent for clusters in the redshift range of our sample and typical image depth of our data. Due to correlated structures this estimate likely gives a lower limit of the true scatter in $\langle \beta \rangle$. We further showed that our method of colour-based distance estimates can reduce this scatter by up to 40 percent. Using the full cluster sample, we showed that our overall mass estimates are robust against moderate changes in the selection parameter β_{cut} and galaxy signal-to-noise threshold. Further, it could be shown that the derived concentrations are consistent with those predicted by the mass concentration relation presented in Bhattacharya et al. (2013), with no significant hint of an underestimation of the derived concentrations. The comparison with literature shows overall agreement with the masses derived for the CCCP or LoCuSS samples, but show lower masses compared to the results in WtG.

As examples for the whole cluster sample, we discussed the results of three clusters in a redshift range from $z = 0.15$ to $z = 0.45$ in greater detail. The weak lensing analyses yielded results which are consistent with previous X-ray and lensing mass estimates.

In case of A907, the weak lensing data disfavour the recent X-ray estimate of Ettori et al. (2010), favouring the results of Nulsen et al. (2010) and Zhang et al. (2008). We also found agreement of the mass estimates based on Suprime-Cam and WFI for the massive cluster RXCJ1347 using very similar cuts.

The weak lensing masses presented in this work are used in the mass calibration of the integrated Comptonization using the APEX-SZ clusters presented in Nagarajan et al. (2018). Together with our SZ analysis (Bender et al. 2016; Nagarajan et al. 2018) and our upcoming X-ray analysis (F. Pacaud et al., in prep.) this work builds one major part of our multifrequency study of APEX-SZ galaxy clusters.

ACKNOWLEDGEMENTS

The authors thank Mischa Schirmer for providing us with the coadded images of the MS0451.6–0305 field. We acknowledge the support of the Max Planck Gesellschaft Faculty Fellowship program and the High Energy Group at MPE. Further, we acknowledge the support of the DFG Cluster of Excellence ‘Origin and Structure of the Universe’, the Transregio program TR33 ‘The Dark Universe’, the Ludwig-Maximilians-Universität, the University of Bonn, and the SFB 956 ‘Conditions and Impact of Star Formation’. This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of

California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration. FP acknowledges support by the German Aerospace Agency (DLR) with funds from the Ministry of Economy and Technology (BMWi) through grants 50 OR 1514 and 50 OR 1608.

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APPENDIX A: MEASUREMENTS WITHOUT PRIOR ON CONCENTRATION PARAMETER

In addition to the weak lensing measurements using the default setting shown in Table 2, we present in Table A1 the results without applying a prior on the concentration parameter. Table A2 shows the results using the S/N -optimized background selection without prior on the concentration.

Table A1. Weak lensing mass estimates for the conservative background selection, for the overdensities $\Delta = 200$ and $\Delta = 500$, without prior on concentration. For the clusters A907, MACSJ1115, and RXCJ1347, the WFI-based masses are listed in the first line, the SUP-based masses are listed in the following line without reciting the cluster name.

| Cluster | R_{200} [Mpc] | c_{200} | M_{200} [$10^{14} M_{\odot}$] | R_{500} [Mpc] | c_{500} | M_{500} [$10^{14} M_{\odot}$] |
|--------------------|------------------------|-------------------------|--------------------------------------|------------------------|-------------------------|--------------------------------------|
| A2744 | $2.09^{+0.13}_{-0.13}$ | $7.2^{+6.95}_{-2.95}$ | $14.16^{+2.81}_{-2.48}$ | $1.41^{+0.07}_{-0.07}$ | $4.86^{+4.92}_{-2.08}$ | $10.87^{+1.72}_{-1.59}$ |
| RXCJ0019.0-2026 | $1.94^{+0.15}_{-0.15}$ | $3.6^{+1.5}_{-1.1}$ | $11.05^{+2.77}_{-2.37}$ | $1.25^{+0.08}_{-0.09}$ | $2.33^{+1.05}_{-0.76}$ | $7.47^{+1.51}_{-1.43}$ |
| A2813 | $2.07^{+0.19}_{-0.18}$ | $2.65^{+1.25}_{-0.95}$ | $13.61^{+4.1}_{-3.25}$ | $1.3^{+0.09}_{-0.09}$ | $1.67^{+0.87}_{-0.65}$ | $8.49^{+1.83}_{-1.67}$ |
| A209 | $2.39^{+0.19}_{-0.16}$ | $1.6^{+0.65}_{-0.5}$ | $19.07^{+4.92}_{-3.58}$ | $1.43^{+0.07}_{-0.07}$ | $0.96^{+0.44}_{-0.33}$ | $10.12^{+1.61}_{-1.44}$ |
| XLSSC 006 | $1.68^{+0.25}_{-0.23}$ | $2.15^{+2.28}_{-1.65}$ | $8.51^{+4.39}_{-3.04}$ | $1.04^{+0.09}_{-0.14}$ | $1.33^{+1.95}_{-1.07}$ | $4.98^{+1.47}_{-1.71}$ |
| RXCJ0232.2-4420 | $1.48^{+0.2}_{-0.2}$ | $15.95^{+22.35}_{-7.2}$ | $4.91^{+2.27}_{-1.73}$ | $1.03^{+0.12}_{-0.12}$ | $11.05^{+15.97}_{-5.1}$ | $4.08^{+1.67}_{-1.31}$ |
| RXCJ0245.4-5302 | $1.47^{+0.22}_{-0.22}$ | $10.35^{+5.65}_{-5.2}$ | $4.93^{+2.56}_{-1.9}$ | $1.01^{+0.13}_{-0.14}$ | $7.08^{+4.01}_{-3.67}$ | $3.95^{+1.78}_{-1.43}$ |
| A383 | $1.6^{+0.13}_{-0.13}$ | $8.7^{+3.8}_{-2.5}$ | $5.62^{+1.49}_{-1.26}$ | $1.09^{+0.08}_{-0.08}$ | $5.92^{+2.69}_{-1.76}$ | $4.42^{+1.05}_{-0.91}$ |
| RXCJ0437.1 + 0043 | $2.02^{+0.24}_{-0.23}$ | $2.9^{+2.35}_{-1.3}$ | $12.54^{+5.02}_{-3.81}$ | $1.28^{+0.12}_{-0.12}$ | $1.84^{+1.64}_{-0.89}$ | $8.01^{+2.39}_{-2.04}$ |
| MS0451.6-0305 | $1.52^{+0.17}_{-0.17}$ | $8.55^{+7.45}_{-3.55}$ | $7.27^{+2.72}_{-2.18}$ | $1.03^{+0.1}_{-0.11}$ | $5.81^{+5.28}_{-2.5}$ | $5.7^{+1.9}_{-1.59}$ |
| A520 | $2.09^{+0.21}_{-0.18}$ | $1.6^{+0.75}_{-0.6}$ | $12.7^{+4.22}_{-3.01}$ | $1.25^{+0.09}_{-0.09}$ | $0.96^{+0.51}_{-0.39}$ | $6.74^{+1.49}_{-1.32}$ |
| RXCJ0516.6-5430 | $2.44^{+0.45}_{-0.27}$ | $0.55^{+0.7}_{-0.5}$ | $22.37^{+14.8}_{-6.63}$ | $1.26^{+0.15}_{-0.22}$ | $0.28^{+0.44}_{-0.26}$ | $7.74^{+3.07}_{-3.37}$ |
| RXCJ0528.9-3927 | $1.87^{+0.25}_{-0.25}$ | $1.3^{+1.35}_{-0.8}$ | $9.94^{+4.54}_{-3.48}$ | $1.09^{+0.12}_{-0.14}$ | $0.76^{+0.91}_{-0.5}$ | $4.89^{+1.72}_{-1.7}$ |
| RXCJ0532.9-3701 | $1.82^{+0.14}_{-0.15}$ | $4.75^{+2.35}_{-1.6}$ | $9.07^{+2.26}_{-2.06}$ | $1.2^{+0.08}_{-0.09}$ | $3.13^{+1.66}_{-1.12}$ | $6.5^{+1.34}_{-1.29}$ |
| A3404 | $1.97^{+0.25}_{-0.22}$ | $4.95^{+2.85}_{-1.9}$ | $10.25^{+4.42}_{-3.06}$ | $1.3^{+0.13}_{-0.13}$ | $3.27^{+2.01}_{-1.33}$ | $7.4^{+2.53}_{-1.96}$ |
| Bullet | $1.92^{+0.24}_{-0.23}$ | $2.55^{+1.55}_{-1.15}$ | $10.9^{+4.62}_{-3.47}$ | $1.2^{+0.12}_{-0.13}$ | $1.6^{+1.08}_{-0.78}$ | $6.72^{+2.31}_{-1.93}$ |
| A907 | $1.54^{+0.24}_{-0.23}$ | $2.9^{+2.55}_{-1.4}$ | $4.82^{+2.62}_{-1.85}$ | $0.98^{+0.12}_{-0.13}$ | $1.84^{+1.78}_{-0.95}$ | $3.08^{+1.28}_{-1.05}$ |
| | $1.56^{+0.2}_{-0.19}$ | $3.65^{+2.6}_{-1.5}$ | $5.01^{+2.19}_{-1.62}$ | $1.01^{+0.1}_{-0.11}$ | $2.36^{+1.83}_{-1.04}$ | $3.4^{+1.13}_{-0.96}$ |
| RXCJ1023.6 + 0411 | $1.88^{+0.1}_{-0.11}$ | $5.3^{+1.3}_{-1}$ | $10.17^{+1.71}_{-1.68}$ | $1.25^{+0.06}_{-0.07}$ | $3.52^{+0.92}_{-0.7}$ | $7.44^{+1.11}_{-1.1}$ |
| MS1054.4-0321 | $1.99^{+0.33}_{-0.44}$ | $16^{+43}_{-12.5}$ | $22.79^{+13.32}_{-12.02}$ | $1.38^{+0.23}_{-0.31}$ | $11.09^{+0}_{-8.83}$ | $18.97^{+11.09}_{-10.07}$ |
| MACSJ1115.8 + 0129 | $1.65^{+0.24}_{-0.25}$ | $1.45^{+2.1}_{-1.05}$ | $7.4^{+3.72}_{-2.88}$ | $0.97^{+0.15}_{-0.23}$ | $0.86^{+1.44}_{-0.66}$ | $3.79^{+2.03}_{-2.09}$ |
| | $1.67^{+0.2}_{-0.21}$ | $3.9^{+2.85}_{-1.8}$ | $7.67^{+3.1}_{-2.55}$ | $1.09^{+0.11}_{-0.12}$ | $2.54^{+2}_{-1.25}$ | $5.28^{+1.79}_{-1.6}$ |
| A1300 | $1.74^{+0.2}_{-0.2}$ | $3.65^{+5.75}_{-2}$ | $8.2^{+3.17}_{-2.52}$ | $1.13^{+0.11}_{-0.12}$ | $2.36^{+4.05}_{-1.37}$ | $5.56^{+1.72}_{-1.54}$ |
| RXCJ1135.6-2019 | $1.62^{+0.18}_{-0.19}$ | $3.4^{+2.1}_{-1.6}$ | $6.61^{+2.46}_{-2.07}$ | $1.04^{+0.1}_{-0.11}$ | $2.19^{+1.47}_{-1.1}$ | $4.41^{+1.32}_{-1.21}$ |
| RXCJ1206.2-0848 | $2.04^{+0.26}_{-0.25}$ | $1.15^{+1.15}_{-0.7}$ | $15.46^{+6.69}_{-5.01}$ | $1.17^{+0.15}_{-0.2}$ | $0.66^{+0.77}_{-0.43}$ | $7.26^{+3.23}_{-3.14}$ |
| MACSJ1311.0-0311 | $1.63^{+0.17}_{-0.17}$ | $6.6^{+3.9}_{-2.35}$ | $8.39^{+2.91}_{-2.36}$ | $1.1^{+0.1}_{-0.1}$ | $4.43^{+2.76}_{-1.65}$ | $6.36^{+1.85}_{-1.59}$ |
| A1689 | $2.62^{+0.1}_{-0.09}$ | $5.15^{+0.9}_{-0.8}$ | $24.51^{+2.92}_{-2.44}$ | $1.74^{+0.05}_{-0.05}$ | $3.41^{+0.63}_{-0.56}$ | $17.84^{+1.7}_{-1.46}$ |
| RXJ1347-1145 | $1.91^{+0.26}_{-0.29}$ | $4.8^{+9.55}_{-2.7}$ | $12.83^{+5.98}_{-5}$ | $1.26^{+0.13}_{-0.15}$ | $3.17^{+6.75}_{-1.88}$ | $9.22^{+3.06}_{-2.88}$ |
| | $2.1^{+0.19}_{-0.18}$ | $5.7^{+3.75}_{-2.3}$ | $17.05^{+5.06}_{-4.02}$ | $1.4^{+0.1}_{-0.1}$ | $3.8^{+2.65}_{-1.61}$ | $12.63^{+2.95}_{-2.61}$ |
| MACSJ1359.2-1929 | $1.51^{+0.25}_{-0.28}$ | $3.1^{+3.8}_{-2.15}$ | $6.31^{+3.68}_{-2.9}$ | $0.96^{+0.15}_{-0.18}$ | $1.98^{+2.67}_{-1.45}$ | $4.11^{+2.15}_{-1.9}$ |
| A1835 | $2.49^{+0.22}_{-0.19}$ | $2.75^{+0.9}_{-0.75}$ | $22.69^{+6.56}_{-4.81}$ | $1.57^{+0.11}_{-0.1}$ | $1.74^{+0.63}_{-0.51}$ | $14.3^{+3.14}_{-2.61}$ |
| RXJ1504 | $1.75^{+0.2}_{-0.2}$ | $3.7^{+2.6}_{-1.5}$ | $7.56^{+2.9}_{-2.31}$ | $1.13^{+0.1}_{-0.11}$ | $2.4^{+1.83}_{-1.04}$ | $5.14^{+1.48}_{-1.34}$ |
| A2163 | $3.07^{+0.32}_{-0.45}$ | $1.1^{+0.85}_{-0.6}$ | $40.28^{+13.95}_{-15.24}$ | $1.75^{+0.17}_{-0.18}$ | $0.63^{+0.56}_{-0.37}$ | $18.59^{+5.77}_{-5.19}$ |
| A2204 | $2.23^{+0.36}_{-0.28}$ | $2.2^{+1.1}_{-0.95}$ | $14.63^{+8.29}_{-4.85}$ | $1.38^{+0.16}_{-0.14}$ | $1.36^{+0.76}_{-0.64}$ | $8.63^{+3.26}_{-2.41}$ |
| RXCJ2014.8-2430 | $1.76^{+0.46}_{-0.38}$ | $3.05^{+6.35}_{-2}$ | $7.18^{+7.23}_{-3.72}$ | $1.12^{+0.2}_{-0.2}$ | $1.95^{+4.47}_{-1.35}$ | $4.65^{+2.96}_{-2.03}$ |
| RXCJ2151.0-0736 | $1.26^{+0.22}_{-0.12}$ | $4.85^{+8}_{-2.95}$ | $3.06^{+1.9}_{-1.48}$ | $0.83^{+0.13}_{-0.16}$ | $3.2^{+5.65}_{-2.05}$ | $2.2^{+1.21}_{-1.04}$ |
| A2390 | $2.03^{+0.12}_{-0.12}$ | $4.8^{+1.45}_{-1.15}$ | $11.96^{+2.25}_{-2}$ | $1.34^{+0.07}_{-0.07}$ | $3.17^{+1.02}_{-0.81}$ | $8.59^{+1.37}_{-1.27}$ |
| MACSJ2214.9-1359 | $1.76^{+0.24}_{-0.25}$ | $4.7^{+4.6}_{-2.1}$ | $10.67^{+4.99}_{-3.93}$ | $1.16^{+0.13}_{-0.14}$ | $3.1^{+3.24}_{-1.46}$ | $7.63^{+2.75}_{-2.46}$ |
| MACSJ2243.3-0935 | $2.1^{+0.21}_{-0.21}$ | $1.6^{+1.6}_{-0.85}$ | $16.97^{+5.62}_{-4.6}$ | $1.25^{+0.12}_{-0.16}$ | $0.96^{+1.09}_{-0.55}$ | $9.01^{+2.9}_{-3}$ |
| RXCJ2248.7-4431 | $2.16^{+0.18}_{-0.18}$ | $2.35^{+1.05}_{-0.8}$ | $16.46^{+4.47}_{-3.78}$ | $1.34^{+0.1}_{-0.11}$ | $1.46^{+0.73}_{-0.54}$ | $9.91^{+2.29}_{-2.15}$ |
| A2537 | $2.1^{+0.16}_{-0.15}$ | $4.05^{+2.1}_{-1.4}$ | $14.28^{+3.52}_{-2.85}$ | $1.37^{+0.08}_{-0.08}$ | $2.64^{+1.48}_{-0.97}$ | $9.91^{+1.84}_{-1.65}$ |
| RXCJ2337.6 + 0016 | $1.94^{+0.17}_{-0.16}$ | $3.05^{+1.3}_{-1.05}$ | $10.97^{+3.14}_{-2.5}$ | $1.24^{+0.09}_{-0.09}$ | $1.95^{+0.91}_{-0.72}$ | $7.11^{+1.61}_{-1.41}$ |

Table A2. Weak lensing mass estimates for the S/N -optimized background selection, for the overdensities $\Delta = 200$ and $\Delta = 500$, without prior on concentration. For the clusters A907, MACSJ1115, and RXCJ1347, the WFI-based masses are listed in the first line, the SUP based masses are listed in the following line without reciting the cluster name.

| Cluster | R_{200} [Mpc] | c_{200} | M_{200} [$10^{14} M_{\odot}$] | R_{500} [Mpc] | c_{500} | M_{500} [$10^{14} M_{\odot}$] |
|--------------------|------------------------|------------------------|--------------------------------------|------------------------|------------------------|--------------------------------------|
| A2744 | $2.04^{+0.12}_{-0.13}$ | $6.65^{+6.6}_{-2.65}$ | $13.17^{+2.46}_{-2.36}$ | $1.37^{+0.06}_{-0.07}$ | $4.47^{+4.67}_{-1.86}$ | $10^{+1.47}_{-1.42}$ |
| RXCJ0019.0-2026 | $2.01^{+0.13}_{-0.13}$ | $3.75^{+1.1}_{-1.05}$ | $12.29^{+2.54}_{-2.23}$ | $1.3^{+0.07}_{-0.08}$ | $2.43^{+0.77}_{-0.73}$ | $8.38^{+1.33}_{-1.4}$ |
| A2813 | $1.96^{+0.18}_{-0.17}$ | $2.15^{+1.1}_{-0.85}$ | $11.56^{+3.49}_{-2.75}$ | $1.21^{+0.09}_{-0.09}$ | $1.33^{+0.76}_{-0.57}$ | $6.77^{+1.55}_{-1.44}$ |
| A209 | $2.35^{+0.17}_{-0.15}$ | $1.70^{+0.65}_{-0.50}$ | $18.13^{+4.23}_{-3.25}$ | $1.41^{+0.07}_{-0.07}$ | $1.02^{+0.44}_{-0.33}$ | $9.83^{+1.49}_{-1.3}$ |
| XLSSC 006 | $1.46^{+0.16}_{-0.16}$ | $4.90^{+3.90}_{-2.20}$ | $5.58^{+2.04}_{-1.64}$ | $0.97^{+0.09}_{-0.09}$ | $3.24^{+2.75}_{-1.54}$ | $4.03^{+1.17}_{-1.07}$ |
| RXCJ0232.2-4420 | $1.52^{+0.22}_{-0.2}$ | $9.1^{+6.9}_{-4.75}$ | $5.32^{+2.66}_{-1.83}$ | $1.04^{+0.12}_{-0.12}$ | $6.2^{+4.89}_{-3.35}$ | $4.2^{+1.67}_{-1.33}$ |
| RXCJ0245.4-5302 | $1.48^{+0.2}_{-0.22}$ | $9.35^{+13.95}_{-4.5}$ | $5.03^{+2.33}_{-1.93}$ | $1.01^{+0.12}_{-0.14}$ | $6.38^{+9.91}_{-3.17}$ | $3.99^{+1.58}_{-1.4}$ |
| A383 | $1.6^{+0.13}_{-0.13}$ | $8.4^{+3.65}_{-2.35}$ | $5.62^{+1.49}_{-1.26}$ | $1.09^{+0.08}_{-0.08}$ | $5.71^{+2.58}_{-1.66}$ | $4.4^{+0.98}_{-0.91}$ |
| RXCJ0437.1 + 0043 | $1.86^{+0.22}_{-0.16}$ | $3.7^{+2.75}_{-1.7}$ | $9.79^{+3.9}_{-2.83}$ | $1.21^{+0.11}_{-0.11}$ | $2.4^{+1.93}_{-1.17}$ | $6.65^{+1.89}_{-1.64}$ |
| MS0451.6-0305 | $1.58^{+0.16}_{-0.16}$ | $8.3^{+6.1}_{-3.1}$ | $8.16^{+2.74}_{-2.24}$ | $1.07^{+0.09}_{-0.1}$ | $5.63^{+4.32}_{-2.19}$ | $6.38^{+1.84}_{-1.62}$ |
| A520 | $2.09^{+0.2}_{-0.17}$ | $1.7^{+0.75}_{-0.6}$ | $12.7^{+4}_{-2.85}$ | $1.26^{+0.08}_{-0.08}$ | $1.02^{+0.51}_{-0.4}$ | $6.88^{+1.44}_{-1.18}$ |
| RXCJ0516.6-5430 | $2.34^{+0.55}_{-0.25}$ | $0.5^{+0.65}_{-0.45}$ | $19.73^{+17.44}_{-5.67}$ | $1.19^{+0.14}_{-0.22}$ | $0.26^{+0.4}_{-0.23}$ | $6.56^{+2.67}_{-3.02}$ |
| RXCJ0528.9-3927 | $1.9^{+0.25}_{-0.2}$ | $0.9^{+0.9}_{-0.85}$ | $10.43^{+4.68}_{-2.96}$ | $1.05^{+0.13}_{-0.16}$ | $0.5^{+0.59}_{-0.48}$ | $4.44^{+1.8}_{-1.77}$ |
| RXCJ0532.9-3701 | $1.89^{+0.13}_{-0.13}$ | $4^{+1.75}_{-1.25}$ | $10.16^{+2.24}_{-1.96}$ | $1.23^{+0.07}_{-0.08}$ | $2.61^{+1.23}_{-0.87}$ | $7.03^{+1.3}_{-1.22}$ |
| A3404 | $1.94^{+0.21}_{-0.2}$ | $5.85^{+3.15}_{-2}$ | $9.79^{+3.53}_{-2.73}$ | $1.3^{+0.11}_{-0.12}$ | $3.91^{+2.22}_{-1.4}$ | $7.28^{+2.1}_{-1.8}$ |
| Bullet | $1.84^{+0.22}_{-0.19}$ | $3.25^{+1.55}_{-1.3}$ | $9.59^{+3.87}_{-2.67}$ | $1.18^{+0.11}_{-0.11}$ | $2.08^{+1.08}_{-0.89}$ | $6.32^{+2}_{-1.62}$ |
| A907 | $1.6^{+0.21}_{-0.21}$ | $3.1^{+2.25}_{-1.35}$ | $5.41^{+2.42}_{-1.86}$ | $1.02^{+0.11}_{-0.11}$ | $1.98^{+1.58}_{-0.92}$ | $3.52^{+1.2}_{-1.05}$ |
| | $1.53^{+0.23}_{-0.2}$ | $2.45^{+2}_{-1.2}$ | $4.73^{+2.47}_{-1.62}$ | $0.96^{+0.1}_{-0.1}$ | $1.53^{+1.39}_{-0.81}$ | $2.88^{+1.03}_{-0.83}$ |
| RXCJ1023.6 + 0411 | $1.83^{+0.09}_{-0.1}$ | $5.65^{+1.35}_{-1.05}$ | $9.38^{+1.45}_{-1.46}$ | $1.22^{+0.06}_{-0.06}$ | $3.77^{+0.95}_{-0.74}$ | $6.94^{+0.99}_{-0.97}$ |
| MS1054.4-0321 | $2.07^{+0.39}_{-0.36}$ | $6.65^{+9.35}_{-5.3}$ | $25.65^{+17.4}_{-11.19}$ | $1.39^{+0.19}_{-0.22}$ | $4.47^{+6.62}_{-3.68}$ | $19.47^{+8.82}_{-7.74}$ |
| MACSJ1115.8 + 0129 | $1.57^{+0.21}_{-0.23}$ | $1.5^{+2.1}_{-1.05}$ | $6.37^{+2.92}_{-2.41}$ | $0.93^{+0.14}_{-0.22}$ | $0.89^{+1.44}_{-0.66}$ | $3.31^{+1.7}_{-1.84}$ |
| | $1.61^{+0.17}_{-0.19}$ | $3.7^{+2.7}_{-1.6}$ | $6.87^{+2.42}_{-2.16}$ | $1.04^{+0.1}_{-0.11}$ | $2.4^{+1.9}_{-1.11}$ | $4.67^{+1.47}_{-1.35}$ |
| A1300 | $1.82^{+0.19}_{-0.19}$ | $2.5^{+2.9}_{-1.35}$ | $9.38^{+3.26}_{-2.64}$ | $1.14^{+0.1}_{-0.12}$ | $1.57^{+2.02}_{-0.91}$ | $5.75^{+1.63}_{-1.57}$ |
| RXCJ1135.6-2019 | $1.53^{+0.16}_{-0.17}$ | $4.15^{+2.45}_{-1.7}$ | $5.57^{+1.94}_{-1.66}$ | $1^{+0.09}_{-0.1}$ | $2.71^{+1.72}_{-1.18}$ | $3.89^{+1.13}_{-1.04}$ |
| RXCJ1206.2-0848 | $2.07^{+0.2}_{-0.19}$ | $1.9^{+1.5}_{-0.85}$ | $16.15^{+5.15}_{-4.05}$ | $1.26^{+0.12}_{-0.13}$ | $1.16^{+1.03}_{-0.56}$ | $9.09^{+2.74}_{-2.49}$ |
| MACSJ1311.0-0311 | $1.61^{+0.16}_{-0.17}$ | $4^{+2.4}_{-1.6}$ | $8.08^{+2.66}_{-2.3}$ | $1.05^{+0.09}_{-0.1}$ | $2.61^{+1.69}_{-1.11}$ | $5.59^{+1.64}_{-1.44}$ |
| A1689 | $2.58^{+0.08}_{-0.08}$ | $5.45^{+0.95}_{-0.75}$ | $23.41^{+2.25}_{-2.11}$ | $1.72^{+0.05}_{-0.05}$ | $3.62^{+0.67}_{-0.53}$ | $17.21^{+1.43}_{-1.36}$ |
| RXCJ1347-1145 | $2.06^{+0.21}_{-0.22}$ | $2.7^{+2.55}_{-1.3}$ | $16.09^{+5.44}_{-4.63}$ | $1.3^{+0.11}_{-0.12}$ | $1.7^{+1.78}_{-0.88}$ | $10.09^{+2.64}_{-2.47}$ |
| | $2.08^{+0.16}_{-0.17}$ | $4.85^{+2.2}_{-1.6}$ | $16.57^{+4.13}_{-3.74}$ | $1.37^{+0.09}_{-0.1}$ | $3.2^{+1.55}_{-1.12}$ | $11.93^{+2.43}_{-2.31}$ |
| MACSJ1359.2-1929 | $1.38^{+0.24}_{-0.28}$ | $2.7^{+4.95}_{-2.25}$ | $4.82^{+2.97}_{-2.38}$ | $0.87^{+0.14}_{-0.24}$ | $1.7^{+3.47}_{-1.48}$ | $3.02^{+1.69}_{-1.89}$ |
| A1835 | $2.42^{+0.2}_{-0.17}$ | $3^{+0.95}_{-0.8}$ | $20.83^{+5.6}_{-4.09}$ | $1.54^{+0.1}_{-0.1}$ | $1.91^{+0.66}_{-0.55}$ | $13.44^{+2.77}_{-2.33}$ |
| RXCJ1504 | $1.68^{+0.18}_{-0.17}$ | $4.05^{+2.2}_{-1.55}$ | $6.69^{+2.39}_{-1.83}$ | $1.1^{+0.09}_{-0.09}$ | $2.64^{+1.55}_{-1.08}$ | $4.64^{+1.29}_{-1.07}$ |
| A2163 | $2.87^{+0.52}_{-0.36}$ | $1.4^{+0.9}_{-0.75}$ | $32.91^{+21.33}_{-10.9}$ | $1.69^{+0.18}_{-0.15}$ | $0.82^{+0.61}_{-0.48}$ | $16.65^{+5.91}_{-4.07}$ |
| A2204 | $2.19^{+0.19}_{-0.26}$ | $2.5^{+1.2}_{-0.6}$ | $13.86^{+3.93}_{-4.37}$ | $1.37^{+0.1}_{-0.14}$ | $1.57^{+0.83}_{-0.41}$ | $8.5^{+1.94}_{-2.3}$ |
| RXCJ2014.8-2430 | $1.59^{+0.33}_{-0.31}$ | $3.1^{+4.05}_{-1.9}$ | $5.29^{+4.03}_{-2.53}$ | $1.02^{+0.17}_{-0.18}$ | $1.98^{+2.84}_{-1.29}$ | $3.44^{+1.99}_{-1.52}$ |
| RXCJ2151.0-0736 | $1.21^{+0.2}_{-0.23}$ | $6.25^{+9.75}_{-3.55}$ | $2.71^{+1.58}_{-1.27}$ | $0.81^{+0.12}_{-0.14}$ | $4.19^{+6.9}_{-2.49}$ | $2.04^{+1.04}_{-0.89}$ |
| A2390 | $2.06^{+0.11}_{-0.11}$ | $4.75^{+1.35}_{-1.05}$ | $12.5^{+2.11}_{-1.9}$ | $1.36^{+0.06}_{-0.06}$ | $3.13^{+0.95}_{-0.74}$ | $8.96^{+1.31}_{-1.2}$ |
| MACSJ2214.9-1359 | $1.89^{+0.22}_{-0.22}$ | $4.35^{+3.10}_{-1.70}$ | $13.21^{+5.17}_{-4.10}$ | $1.24^{+0.11}_{-0.12}$ | $2.85^{+2.18}_{-1.18}$ | $9.31^{+2.81}_{-2.44}$ |
| MACSJ2243.3-0935 | $2.13^{+0.20}_{-0.20}$ | $1.30^{+1.20}_{-0.65}$ | $17.71^{+5.47}_{-4.53}$ | $1.24^{+0.12}_{-0.15}$ | $0.76^{+0.81}_{-0.41}$ | $8.72^{+2.79}_{-2.77}$ |
| RXCJ2248.7-4431 | $2.29^{+0.16}_{-0.17}$ | $2.05^{+0.75}_{-0.6}$ | $19.61^{+4.41}_{-4.05}$ | $1.41^{+0.08}_{-0.1}$ | $1.26^{+0.51}_{-0.4}$ | $11.32^{+2.14}_{-2.15}$ |
| A2537 | $2.16^{+0.13}_{-0.13}$ | $4.3^{+1.85}_{-1.25}$ | $15.54^{+2.98}_{-2.64}$ | $1.42^{+0.07}_{-0.07}$ | $2.82^{+1.3}_{-0.87}$ | $10.92^{+1.71}_{-1.53}$ |
| RXCJ2337.6 + 0016 | $1.94^{+0.17}_{-0.16}$ | $3.05^{+1.30}_{-1.05}$ | $10.97^{+3.14}_{-2.50}$ | $1.24^{+0.09}_{-0.09}$ | $1.95^{+0.91}_{-0.72}$ | $7.11^{+1.61}_{-1.4}$ |

APPENDIX B: COLOUR COMPOSITE IMAGES WITH WEAK LENSING CONVERGENCE CONTOURS

We provide RGB colour images with weak lensing contours for the central regions of all clusters presented in this work as online only

supplementary data. As example for the available material we show in Fig. B1 the RGB colour image, with contours for the cluster RXCJ1135.6-2019. One of the two outliers discussed in Nagarajan et al. (2018).

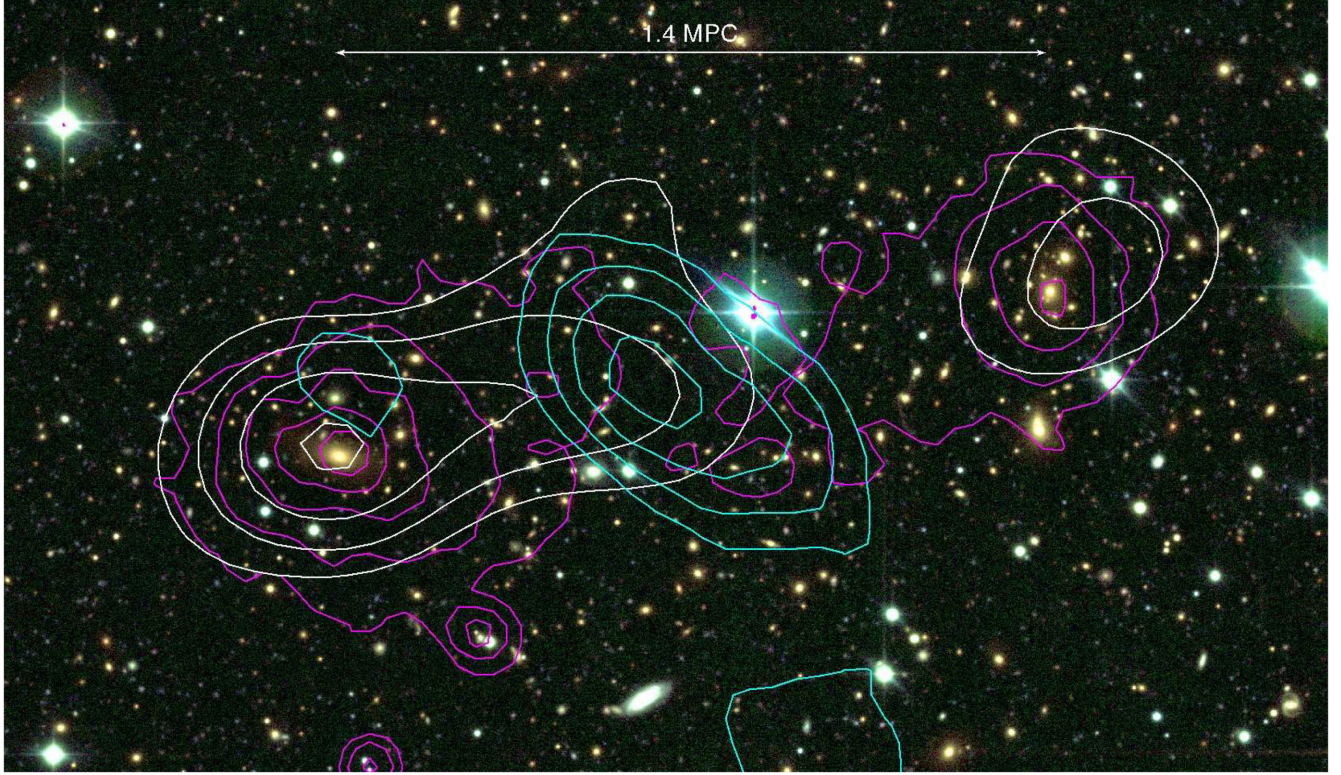


Figure B1. RXCJ1135.6-2019: Colour composite image with lensing convergence contours in white, XMM surface brightness contours in magenta, and SZ contours in cyan (top panel), XMM surface brightness map with lensing convergence contours. Note: SZ contours only indicative. This cluster is an SZ non-detection when centred on the BCG.

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